Department ELEC : 
Fundamental Electricity and 
Instrumentation

ANNUAL REPORT 2014

Editor:
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Dept. Elec, Faculty of Engineering
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1. Introduction to the department ELEC

1.1 INTRODUCTION TO THE LONG TERM STRATEGY OF THE DEPARTMENT ELEC

'ELEC' stands for "Fundamental Electricity and Instrumentation" (in Dutch: "Algemene Elektriciteit en Instrumentatie") and the name corresponds to the educational and research tasks and objectives of the department. The main research activity of the department is the development of new measurement techniques using advanced signal processing methods, embedded in an identification framework. When we make a measurement, we have to make a number of decisions: firstly a model for the considered part of reality is proposed (e.g. for a resistance measurement Ohm’s law can be selected, describing the relation between the voltage across the resistor and the current through it); next a number of measurements is made (e.g. a number of current and voltage measurements); finally the quantities of interest are extracted from these measurements by matching the model to the data. Often an intuitive approach is used. However, in the presence of measurement errors this can lead to a very poor and even dangerous behaviour: the user wouldn't remark that something is going seriously wrong. This is the major motivation for the development of the identification theory. It offers a systematic approach to 'optimally' fit mathematical models to experimental data, eliminating stochastic distortions as much as possible. As such it can be considered as the modern formulation of the measurement problem, and for that reason the identification approach is the “fil rouge” in most of the activities of the department.

Each measurement (or identification session) consists of a series of basic steps:

- Collect information about the system;
- Select a (non) parametric model structure to represent the system;
- Select the model parameters to fit the model as well as possible to the measurements (this requires a “goodness of fit” criterion);
- Validate the selected model.

Most of the research activities of the department are related to one of these problems, but this does not narrow our focus. At this moment we deal with a very wide scope of application fields:

- Systems covering the frequency range from a few MHz up to 50 GHz,
- Linear systems, non-linear systems and time varying systems
- Lumped systems and distributed systems.
We applied the measurement and modelling techniques to the identification of electrical machines (frequency range 0.01 Hz till 1 kHz, linear models, 2 inputs and 2 outputs), mechanical vibrating systems (frequency range below 5 kHz, linear or non-linear, up to 2 inputs/2 outputs), electronic circuits and filters (frequency range up to 5 MHz, linear and non-linear models, single input/single output or multiple input/multiple output), underwater acoustics (frequency range up to a few MHz, 1 input and 2 outputs), distributed systems (telecommunication lines, up to a few hundreds MHz), microwave applications (frequency range up to 50 GHz, non-linear, 6-port measurements). Since a few years we apply those methods also to the analysis of biological samples used as records of global climate change. For some of these applications the efforts are focused on the development of new measurement instruments (measurement of telecommunication lines, non-linear microwave analyser), for others we focused completely on the development of new data processing and modelling techniques, or even worked on the underlying fundamental theoretical aspects.

To cover this wide application range, we make use of an extensive measurement park. Most of it nowadays consists of VXI-or PXI-based data-acquisition systems, although we have also some classical instruments like network and spectrum analysers. All these instruments are computer controlled in a Matlab™ environment.

1.2 RESEARCH TOPICS OF THE DEPARTMENT ELEC (2014)

- Telecommunication: applications (see page 40)
- System identification and parameter estimation of linear, nonlinear and time varying systems (see page 41)
- Identification of time- and parameter-varying systems (see page 59)
- Experiment design (see page 67)
- Time and frequency domain system identification (see page 69)
- Structured Low-rank approximation (see page 72)
- Modelling high frequency nonlinear systems (see page 74)
- High frequency design and characterization (see page 76)
- Medical Measurements and Signal Analysis (see page 81)
The mixed girls/boys team was founded in 2010, sponsored by the ELEC department. It quickly became clear that some practice might come in handy, and the weekly ELEC futsal training sessions were born. Everyone was and is welcome to join, and we only play the sport to have some fun.

Over the years, ELEC was complemented with some fine new Phd. students, who were not completely tired and fat yet. The combination with the weekly training sessions allowed our team to rise from the very bottom of the competition to at least an above-average rating. Practice makes perfect!

Also, it turns out ice cream is a pretty good motivator...
1.4 STAFF OF ELEC (STATUS 01/03/2015)

1.4.1 General Director of the dept. ELEC

**Johan Schoukens** received both the degree of master in electrical engineering in 1980 and the degree of doctor in engineering (PhD) in 1985 from the Vrije Universiteit Brussel (VUB), Brussels, Belgium. In 1991 he received the degree of Geaggregeerde voor het Hoger Onderwijs from the VUB, and in 2014 the degree of Doctor of Science from The University of Warwick. From 1981 to 2000, Johan Schoukens was a researcher of the Belgian National Fund for Scientific Research (FWO-Vlaanderen) at the Electrical Engineering (ELEC) Department of the Vrije Universiteit Brussel (VUB) where he is currently a full-time professor in electrical engineering. Since 2009 he is visiting professor at the department of Computer Sciences of the Katholieke Universiteit Leuven. His main research interests include system identification, signal processing, and measurement techniques. Johan Schoukens has been a Fellow of IEEE since 1997. He was the recipient of the 2002 Andrew R. Chi Best Paper Award of the IEEE Transactions on Instrumentation and Measurement, the 2002 Society Distinguished Service Award from the IEEE Instrumentation and Measurement Society, and the 2007 Belgian Francqui Chair at the Université Libre de Bruxelles (Belgium). Since 2010, he is a member of Royal Flemish Academy of Belgium for Sciences and the Arts. In 2011 he received a Doctor Honoris Causa degree from the Budapest University of Technology and Economics (Hungary). Since 2013, he is a honorary professor of the university of Warwick.

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1.4.2 Professor members of the dept. ELEC

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**Rik Pintelon** was born in Gent, Belgium, on December 4, 1959. He received a master's degree in electrical engineering in 1982, a doctorate (PhD) in engineering in 1986, and the qualification to teach at university level (geaggregeerde voor het hoger onderwijs) in 1994, all from the Vrije Universiteit Brussel (VUB), Brussels, Belgium. In 2014 he received the degree of Doctor of Science (DSc) from the University of Warwick (UK) for publications with the collective title "Frequency Domain System Identification: A Mature Modeling Tool". From 1982 to 1984 and 1986 to 2000, Dr. Pintelon was a researcher with the Belgian National Fund for Scientific Research (FWO-Vlaanderen) at the Electrical Engineering (ELEC) Department of the VUB. From 1984 to 1986 he did his military service overseas in Tunisia at the Institut National Agronomique de Tunis. From 1991 to 2000 he was a part-time lecturer at the department ELEC of the VUB, and since 2000 he is a full-time professor in electrical engineering at the same department. Since 2009 he is visiting professor at the department of Computer Sciences of the Katholieke Universiteit Leuven, and since 2013 he is a honorary professor in the School of Engineering of the University of Warwick. His main research interests include system identification, signal processing, and measurement techniques. Dr. Pintelon is the coauthor of 4 books on System Identification and the coauthor of more than 200 articles in refereed international journals. He has been a Fellow of IEEE since 1998. Dr. Pintelon was the recipient of the 2012 IEEE Joseph F. Keithley Award in Instrumentation and Measurement (IEEE Technical Field Award).

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**Yves Rolain** (1961, Belgium) received the Electrical Engineering (Burgerlijk Ingenieur) degree in July 1984, the degree of computer sciences in 1986, and the PhD degree in applied sciences in 1993, all from the Vrije Universiteit Brussel (VUB), Brussels, Belgium. He is currently a research professor at the VUB in the department ELEC. He became a fellow of the IEEE in 2006 and received the IEEE I&M Society award in 2005. His main interests are microwave measurements and modelling, applied digital signal processing and parameter estimation / system identification.

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Leo Van Biesen was born in Elsene, Belgium, on August 31, 1955. He received the degree of Electro-Mechanical Engineer from the Vrije Universiteit Brussel (VUB), Brussels in 1978, and the Doctoral degree (PhD) from the same university in 1983. Currently he is a full senior professor. He teaches courses on fundamental electricity, electrical measurement techniques, signal theory, computer-controlled measurement systems, telecommunication, underwater acoustics and Geographical Information Systems for sustainable development of environments. His current interests are signal theory, modern spectral estimators, time domain reflectometry, wireless local loops, XDSL technologies, underwater acoustics, and expert systems for intelligent instrumentation.

He has been chairman of IMEKO TC-7 from 1994-2000 and President Elect of IMEKO for the period 2000-2003 and the liaison Officer between the IEEE and IMEKO. Prof. Dr. Ir. Leo Van Biesen has been president of IMEKO until September 2006. He is also member of the board of FITCE Belgium and of USRSl Belgium.

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Gerd Vandersteen Gerd Vandersteen was born in Belgium in 1968 and received the degree in electrical engineering from the Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1991. In 1997, he received his PhD in electrical engineering, entitled "Identification of Linear and Nonlinear Systems in an Errors-in-Variables Least Squares and Total Least Squares Framework", from the Vrije Universiteit Brussel/ ELEC.

During his postdoc, he worked at the micro-electronics research centre IMEC as Principal Scientist in the Wireless Group with the focus on modeling, measurement and simulation of electronic circuits in state-of-the-art silicon technologies. This research was in the context of a collaboration with the Vrije Universiteit Brussels.

From 2008 on, he is working as Prof. at the Vrije Universiteit Brussels/ELEC within the context of measuring, modeling and analysis of complex linear and nonlinear system. Within this context, the set of systems under consideration is extended from micro-electronic circuits towards to all kinds of electro-mechanical systems.

From 2011 on, he is director of the Doctoral School of Natural Sciences and (Bioscience) Engineering (NSE)

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1.4.3  Postdoc. members of the dept. ELEC

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He obtained the Doctoral degree (Ph.D.) from the Vrije Universiteit Brussel (VUB), Brussels in 2010. Currently, he is a post-doctoral researcher at Department ELEC/ VUB, Belgium. His current research focuses on linear and nonlinear system identification.

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Ebrahim Louarroudi was born in Antwerp (Mortsel), Belgium, on May 29, 1985. He received the degree of Electromechanical Engineering in July 2009 from the Vrije Universiteit Brussel, Belgium. He joined the department ELEC as a PhD researcher in October 2009. Currently, he is working as a Post-Doc researcher in the field of system identification. His main interests include different measurement and identification techniques for (periodically) time-varying systems and their relevances in practice. In 2014, he received "The Martin Black Prize" for the best paper published in the journal Physiological Measurement of IOP in 2013.

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Anna Marconato was born in Trento, Italy, on April 8th, 1980. She received the B.Sc. in Mathematics and the M.Sc. in Telecommunication Engineering from the University of Trento, Italy, in 2002 and 2005, respectively. In 2009 she was awarded a joint PhD degree from the University of Trento, Italy, and the Vrije Universiteit Brussel, Belgium. From September 2009 she has been a post-doctoral researcher at Department ELEC, Vrije Universiteit Brussel, Belgium. Her main research interests are in the fields of linear and nonlinear system identification and machine learning.

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Julian Stoev was born on July 1, 1969. He got a M.Sc in 1996 in Electrical Engineering from Sofia Technical University, Bulgaria, and a PhD in Control Engineering in 2003 from Seoul National University, Korea. He worked in the industrial R&D and academia. From 2004 to 2008 he was employed by Samsung Electronics in their headquarters in Suwon, Korea. From 2008 to 2009 he was a research associate at Fraunhofer-Institut für Techno- und Wirtschaftsmathematik in Kaiserslautern, Germany. Starting 2009 and currently he is also a senior researcher at Flanders’ MECHATRONICS Technology Centre, Leuven, Belgium. His scientific interests are related to identification and control of mechatronics systems.

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1.4.4 PhD scholarships ELEC

Georgios Birpoutsoukis was born on October 9, 1986 in Athens, Greece. He received the Mechanical engineering degree in 2010 from the Aristotle University of Thessaloniki. In 2011 he started the M.Sc. program Systems & Control (DCSC) at Delft University of Technology, the Netherlands. He received his degree in 2013. Since January 2014 he has joined the ELEC department as a Ph.D student at Vrije Universiteit Brussel, Belgium. His main interests lie in the field of optimal experiment design for structured nonlinear system identification.

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Piet Bronders was born in Suva (Fiji) in 1991. He graduated as an Electrical Engineer in Electronics and Information Technology in 2014 at the Vrije Universiteit Brussel (VUB). In October 2014 he joined the department ELEC as a PhD student. His main interest is NL RF circuit design and measurement. His current research topic is the design and modelling of RF power amplifiers.

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Matthias Caenepeel was born in Brasschaat, Belgium on August 2, 1989. He received the degree of Electrical Engineer in Electronics and Information Processing in July 2012 from the Vrije Universiteit Brussel, Belgium. In September 2012 he joined the department ELEC as a PhD student. In September 2013 he started a joint PhD (cotutelle) with the department APICS from INRIA Sophia-Antipolis. His research focuses on macromodels and the design of microwave filters.

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Adam Cooman was born in Belgium in 1989. He graduated as an Electrical Engineer in Electronics and Information Processing in 2012 at Vrije Universiteit Brussel (VUB) and joined the Department ELEC as a Ph.D. student later that year. In January 2013, he obtained a grant from the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) to develop analysis and design techniques aimed at non-linear distortion in electronic circuits. His main interests are the design of Electronic circuits, from low frequencies up to the microwave frequencies, and playing some great soccer with the colleagues of ELEC.

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Péter Zoltán Csурcsia was born in Budapest, Hungary, on 17.05. 1985. He obtained his Bachelor of Engineering diploma (BEng in EE, summa cum laude) and his Technical Teacher diploma (Ed in EE, summa cum laude) from Budapest Tech in 2007 and 2008. Parallel with Electrical Engineering he studied technical informatics at Budapest Tech between 2004 and 2008. From 2008 he was a student at the Budapest University of Technology and Economics (BUTE) and at Vienna University of Technology. He graduated in MSc in Embedded Systems and in Applied Informatics (MSc, summa cum laude) in 2010. Now, he is a doctoral student at the BUTE (his advisor Prof. Dr. István Kollár) and at the Vrije Universiteit Brussel (with Prof. Dr. ir. Johan Schoukens). He worked as an IT Teacher from 2006-2010 and as a Program/Web designer. His research interests cover the topics of system identification, digital signal processing, software and and internet technologies.

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Introduction to the department ELEC

Alexander De Cock was born in Brussels (Jette), Belgium, on the 29th of April, 1989. He received the degree of Master of Science: Engineering Sciences: Electronics and Information Technology in September 2012 from the Vrije Universiteit Brussel (Belgium). While his thesis was focused on the application of l1-regularisation in the context of frequency domain identification, his main interest is now optimal experiment design for the identification of structured nonlinear system.

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Jan Decuyper was born in Jette (Belgium) in 1991. He graduated as an Electromechanical Industrial Engineer (Renewable Energy) at the Erasmus Hogeschool Brussel in 2013. In October 2013, he joined the department of INDI as a phd student. As of February 2014, he became a member of the ELEC department. His main research interests are in the field of modelling systems that are subjected to vortex-induced vibrations.

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Alireza Fakhrizadeh Esfahani was born in Esfahan (Iran). He graduated in Electrical Power Engineering. He continued his studies in Technomathematics (Applied Math.) at Master level in Finland and graduated in 2012. He joined the ELEC Department in Sept. 2013. His research area is System Identification under supervision of Prof. Johan Schoukens. He is interested in System Identification, Nonlinear Dynamics and Control. At the moment he is studying the structure detection of nonlinear systems.

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Egon Geerardyn was born on April 15th, 1988 in Jette (Brussels), Belgium. He graduated as an Electrical Engineer in Electronics and Information Theory (profile Measurements, Modelling and Simulations) in 2011 at the Vrije Universiteit Brussel. In October 2011 he joined the department ELEC as a PhD student. His main interests comprises system identification of linear and nonlinear systems, workflow automation and Linux.

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Jan Goos was born in Geel (Belgium) in 1986. He graduated from the Katholieke Universiteit Leuven as an engineer in Computer sciences (Artificial Intelligence) in 2009 and in Mathematical Engineering in 2011. In October 2011 he joined the department of ELEC as a PhD student. His main interests are the measurement and modeling of Linear Parameter Varying (LPV) systems, but he also loves non-linear dynamics.

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Gabriel Hollander was born in Brussels in 1988. In 2012, he graduated the Master's Degree in Pure Mathematics at the University of Ghent. In May 2014, he joined the department ELEC at the VUB as a PhD student. His main research interest are the identification of non-linear systems using block-oriented models.

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Vladimir Lazov was born in Skopje, R. of Macedonia, on June 9th, 1984. He received his Diploma in Electrical Engineering from the Ss. Cyril and Methodius University in Skopje, Republic of Macedonia, in 2010. His specialization and professional field of interest is in Electronics and Telecommunication. Prior to joining ELEC at VUB in June 2014, he worked as a researcher at Katholieke Universiteit Leuven, Belgium at the Faculty of Electrical Engineering division TELEMIC. Currently, Vladimir's research is focused on developing unified models and performing analysis for the compensation of non-idealities using within telecom applications.

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Hannes Maes was born in Hasselt (Belgium) on May 17, 1990. He received the degree of Electrical Engineer in Electronics and Information Processing in July 2012 from the Vrije Universiteit Brussel, Brussels, Belgium. In September 2012 he joined the department ELEC as a PhD student. His main interests are system modeling for biomedical applications and non linear modeling.

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Mayank was born in January 4, 1990, in India. He did his M.Sc. in Applied Mathematics in 2012 from Indian Institute of Technology Roorkee, India. His current research interests are in the field of linear algebra, structured low-rank approximation.

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Leonidas Niyonkuru was born in Maramvya, Burundi on the 17th March 1968. He received the degree of Master of Science in Telecommunication in June 1995 from the Bonch-Bruevich Saint Petersburg State University of Telecommunication in Russia. He worked as teacher assistant at University of Burundi from July 1999 to December 2008. He worked with ECONET wireless Burundi from December 2008 to March 2012. He returned to university of Burundi in March 2012. He joined the department ELEC as a PhD student in February 2015. His research focuses on challenges and solutions of 5G communication system in rural regions.

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Rishi Relan was born in (Rohtak/Haryana) India in 1979. He graduated with a Bachelor of Technology (Honours) degree in Instrumentation and Control Engineering from Kurukshetra University in India. He holds a Master of Science (Cum Laude) degree in Artificial Intelligence from Katholieke Universiteit Leuven in Belgium and a Master of Science (Very Good) degree in Mechatronics from University of Applied Sciences Ravensburg-Weingarten in Germany. Prior to joining ELEC, he worked as a researcher at the Rolls-Royce University Technology Centre (UTC) in the University of Sheffield, U.K, as a research fellow in the Indian Institute of Technology Delhi (IITD) in India and as a Resident engineer for dSPACE GmbH in International Technology & Research Centre of General Motors Europe in Germany. He has also worked for around 2 years in industrial automation sector in India developing solution for textile industries. His main interests are in Statistical signal processing, System identification, Machine learning, intelligent control of mechatronic systems and their applications in automotive, aerospace as well as energy sector.

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Maarten Schoukens was born in Jette (Belgium) in 1987. He graduated as an Electrical Engineer in Electronics and Information Processing (profile Measurement and Modeling of Dynamic Systems) in July 2010 at the Vrije Universiteit Brussel. In September 2010 he joined the department ELEC as a PhD student. His main interests are in the field of nonlinear block oriented system identification of multiport microwave systems.

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Koen Tiels was born in Halle (Belgium) in 1987. He graduated as an Electrotechnical-Mechanical Engineer in July 2010 at the Vrije Universiteit Brussel. In September 2010 he joined the ELEC department as a PhD student. His main interests are in the field of nonlinear block structured system identification.

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David Oliva Uribe was born on May 24th 1975, Mexico City, Mexico. His research interests are in the field of system identification techniques for piezoelectric transducers, in particular the characterization of biological tissues using tactile sensors in medical applications. He graduated with Honours in Electronic and Communication Engineering in 1997 and obtained a Master in Sciences with Specialization in Manufacturing Systems in 2000, both from Tecnológico de Monterrey in Mexico City. From April 2007 to December 2010 he worked as Team Leader of the Research Group of Medical Engineering and Mechatronic Systems at the Institute of Dynamics and Vibrations Research from the Leibniz University of Hannover. Since January 2011, he joined the Department ELEC, Vrije Universiteit Brussel, where he is working toward a joint PhD degree.

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Diana Ugryumova was born in Kiev, Ukraine, on October 26th, 1984. She received the degree in Applied Mathematics (chair of Mathematical Theory of Systems and Control) at the University of Twente in the Netherlands in March 2010. Diana joined the department of ELEC in May 2010 as a PhD student. Her current research is about identification of distillation columns. The aim of this research is to enhance the performance of a distillation column through a better modeling and control strategy.

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Dieter Verbeke was born in Leuven, January 22, 1990. He graduated from KU Leuven with a degree in Mechanical Engineering in 2013. After having worked as a product development engineer with Siemens PLM for one year, Dieter joined the department ELEC as a PhD student in October 2014. His research focuses on the development of a user-friendly methodology to identify systems with a large number of inputs and outputs.

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Mark Vaes was born on September 19th, 1985 in Marche-en-Famenne (Belgium). He graduated as an Industrial Engineer in Electromechanics at the Erasmushogeschool Brussel. In February 2013 he joined the department ELEC as a PhD student. His main interests are in the field of system identification of linear and nonlinear systems.

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Evi Van Nechel was born in Asse (Belgium) on May 15, 1991. She graduated as an Electrical Engineer in Electronics and Information Technology at the Vrije Universiteit Brussel in July 2014. In October 2014, she joined the department of ELEC as a PhD student. Her main research interests are in the field of RF design and modeling of microwave structures.

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Maral Zyari was born in Tehran, Iran in 1986. She graduated as an Electrical Engineer in Electronics and Information Processing in July 2013 at Vrije Universiteit Brussel (VUB). In September 2013 she joined the department ELEC as a PhD student. Her main interests are RF circuit design and her current research is about nonlinear modelling and measuring of high frequency measurement equipment.

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1.4.5 Technical and Administrative Staff

Wim Delcourte  
Wim Delcourte was born in 1962 (Belgium). He graduated as an Industrial Engineer (Industrieel Ingenieur) in 1987. Since May 1989 he is with the department ELEC of the Vrije Universiteit Brussel (VUB full time tenure). Actually he is responsible for the design of electronic measurement instruments for research and education, for the repair and maintenance of complex measurement instruments and computers (20%). He also takes care of the management of the computerrooms of the faculty (80%), and provides ICT support at the engineering faculty.

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Johan Pattyn  
was born in 1974 (Belgium). After 2 years of engineering studies he joined the navy to become a radar technician. Since december 2009 he is with the department ELEC of the Vrije Universiteit Brussel (full time tenure). He is responsible for Rapid PCB Prototyping and also is involved in the maintenance and repair of the instruments and circuits for the students lab's.

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Ann Pintelon  
was born in October 1963 (Belgium). In 1985 she received the Ms degree in Physical Education (VUB). Since 1990 she has been with the department ELEC at the Vrije Universiteit Brussel on a GOA contract (Measurement, Modelling and Identification of Dynamic Systems), between 2008 and 2011 she has been working on the contract "Methusalem": Centre for Data Based Modelling and Model Quality Assessment (4/5 tenure), and since March 2011 a 90% tenure at the university. She is mainly responsible for the scientific reports of the department ELEC (annual report, web-pages ELEC, ...); the management of the infocentre (library, publication list, ...); the administrative organisation of conferences, workshops and doctoral school; hosting of visiting researchers.

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Sven Reyniers  
was born in 1973 (Belgium). He has several years of ICT - experience in multinationals, including several international missions (France, Germany). Since 2006, he is working at the Vrije Universiteit Brussel (full time tenure) at the department ELEC. As system and network administrator he is responsible for the health and availability of the department servers and network.

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Annick Schreyers  
was born in Oudergem (Belgium). In 1983 she obtained the degree of ‘Gegradueerde in de arbeidstherapie’ from the ‘Hoger instituut voor paramedische beroepen’, Gent, Belgium. In January 2014 she joined the department ELEC, as a part-time secretary. She is mainly responsible for the financial administration of the department.

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1.4.6 Professors Emeriti

Alain Barel was born in Roeselare, Belgium, on July 27, 1946. He received the degree in Electrical Engineering from the Université Libre de Bruxelles, Belgium, in 1969, the Postgraduate degree in telecommunications from Rijks Universiteit Gent (State University of Gent), Belgium, in 1974, and the doctor of applied science from the Vrije Universiteit Brussel in 1976. He worked as assistant and Lecturer at the Vrije Universiteit Brussel (VUB). From 2006 until September 2011 he has been 10% active at the department as Professor emeritus and teaches microwaves, and until September 2012 been active as a voluntary researcher at the dept. ELEC.

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Michel Gevers was born in Antwerp, Belgium, in 1945. He obtained an Electrical Engineering degree from the Université Catholique de Louvain, Belgium, in 1968, and a Ph.D. degree from Stanford University, California, in 1972. He holds a Honorary Degree from the Vrije Universiteit Brussel and the University of Linköping, Sweden, and a few other titles. He has been President of the European Union Control Association (EUCA) from 1997 to 1999, and Vice President of the IEEE Control Systems Society in 2000 and 2001. Between 1990 and 2010 he has been the coordinator of the Belgian Interuniversity Network DYSCO (Dynamical Systems, Control, and Optimization) funded by the Federal Ministry of Science. His research interests are in system identification and its interconnection with robust control design, optimal experiment design, data-based control design, optimal control and filtering, and realization theory. He has published about 250 papers and conference papers, and two books: "Adaptive Optimal Control - The Thinking Man’s GPC", by R.R. Bitmead, M. Gevers and V. Wertz (Prentice Hall, 1990), and "Parametrizations in Control, Estimation and Filtering Problems: Accuracy Aspects", by M. Gevers and G. Li (Springer-Verlag, 1993). Until September 2012 he was 20% active at the department ELEC as Professor emeritus, and now still active as a voluntary researcher at the dept. ELEC.

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Ronny Van Loon (1940-2012) obtained a degree in Physics at the ULB, and a PhD in Science at the VUB. He joined the VUB in 1970 as assistant, then Professor at the Faculty of Applied Science. In parallel with the teaching activities, he had research and logistic activities as a medical physicist at the university hospital AZ-VUB: from 1982 on in the Radiotherapy department focusing on EC granted projects in Hyperthermia, from 1989 on in the Radiology department involved in dosimetry and quality assurance. He directed the subgroup QUARAD ("Quality in Radiology"), a team involved in dosimetry, radiation protection and quality improvement in radiology. This group is acting in Belgium as reference centre for the Quality Assurance of the technical aspects of breast cancer screening. Prof. Van Loon was the Past-President of the Belgian Hospital Physicist Association, and member of the Board of the “Federal Agency of Nuclear Control” and the “Belgian Society of Radioprotection”. He was delegate of the VUB in the VLIR-cooperation and Development Cell, and coordinates a cooperation project in Hanoi (Vietnam) and in VLIR International Training programme on Medical Physics.

Until September 2005, he was still 10% active at the department ELEC as professor emeritus. He also contributed to the IAEA’s (International Atomic Energy Agency) teaching programs on radiation protection in medical applications of ionizing radiation. He was scientific advisor at the “Belgian Museum of Radiology”, Brussels, and he was active as a voluntary researcher at the dept. ELEC. In October 2008, he received the title of “Doctor Honoris Causa” from the Hanoi University of Technology.

On 20 December 2012, prof. dr. em. Ronald Van Loon suddenly passed away. We will remember him as a warm friendly and very wise colleague, who remained actively involved at the faculty of Engineering and the university. He always defended his opinion and his philosophical beliefs. He was loyal to the basic philosophy of the Vrije Universiteit Brussel: the principle of “free inquiry”, based on a text of Henri Poincaré, and the principle that the institution must be managed according to the model of democracy.
1.4.7 List of phone numbers and e-mail addresses (Status 01/03/2015)

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<td>+32(0)2 629 28 68</td>
<td><a href="mailto:Julian.Stoev@vub.ac.be">Julian.Stoev@vub.ac.be</a></td>
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<td><a href="mailto:Koen.Tielas@vub.ac.be">Koen.Tielas@vub.ac.be</a></td>
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<tr>
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<td><a href="mailto:dugryumo@vub.ac.be">dugryumo@vub.ac.be</a></td>
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<tr>
<td>L. VAN BIESSEN</td>
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</tr>
<tr>
<td>G. VANDERSTEEN</td>
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</tr>
<tr>
<td>M. ZYARI</td>
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<td><a href="mailto:mzyari@vub.ac.be">mzyari@vub.ac.be</a></td>
</tr>
</tbody>
</table>
1.4.8 Industrial Partnership

- ir. Frank LOUAGE, MSc Zobeida Cisneros Barros; Address System N.V.
- Dr. ir. Luc PEIRLINCKX, TomTom, Belgium, Cap Gemini, Belgium
- ir. Serge TEMMERMAN, SEBA service NV (measuring instruments for telecom. cables)
- Dr. Frank UYTDENHOUWEN, Banana-Telecom
- Dr. ir. Marc VANDEN BOSSCHE, Dr. ir. Frans Verbeyst; NMDG Engineering bvba
- Dr. Lieven Philips, Dr. Adnan Al-Adnani, Dr. Lee Barford; Agilent Technologies

1.4.9 National or international contacts

1.4.9.1 Visiting professors/researchers

- Tadeusz DOBROWIECKI, Budapest University of Technology and Economics, Department of Measurement and Information Systems, Budapest, Hungary: 26/08/2014 – 29/08/2014;


- **Hisham EL MOAQET**, University of Michigan, USA, 17/05/2014 – 17/07/2014


- **Keith GODFREY**, University of Warwick, School of Engineering, UK: 23/06/2014: external examiner technical defence PhD Ebrahim Louarroudi; and 05/09/2014 public defence PhD Ebrahim Louarroudi “Frequency Domain Measurement and Identification of Weakly Nonlinear Time-Periodic Systems”.


- **Sándor KOLUMBÁN**, Budapest University of Technology and Economics, Department of Measurement and Information Systems, Budapest, Hungary: 27/01/2014 – 24/03/2014, research in the frame of PhD.


• **Jean LUKWESA KAIMDU**, University of Kinshasa, Congo, 02/09/2014 – 02/12/2014, Stage VLIR-IUS Congo.


• **Kaushik MAHATA**, University of Newcastle, Australia: 30/04/2014 – 01/07/2014


• **Guillaume MERCÈRE**, University of Potiers, France: 06/05/2014 – 07/05/2014. Presentation at ELEC seminar "Model identification using 'H_infty'-norm-based optimization algorithms: some new developments”

• **Joséphine MPOLE BYOKAME**, University of Kinshasa, Congo, 02/09/2014 – 02/12/2014, Stage VLIR-IUS Congo.


• **Martine Olivi**, Centre de recherche INRIA Sophia-Antipolis Méditerranée, INRIA-APICS, 22/04/2014 – 25/04/2014


• **Fabien SEYFERT**, Centre de recherche INRIA Sophia-Antipolis Méditerranée, INRIA-APICS, 22/04/2014 – 25/04/2014


• **Jérémy VAYSSETTES**, ONERA, the French Aerospace Lab, Toulouse, France: 05/05/2014 – 09/05/2014
• Robbert VOORHOEVE, Eindhoven University of Technology, Netherlands, 10/05/2014 – 07/06/2014. Doctoral School VUB – Dept. ELEC: Identification of Nonlinear Dynamic Systems

• David WESTWICK, Department of Electrical and Computer Engineering, University of Calgary, Canada: 19/05/2014 – 06/06/2014.

• Miro ZIVANOVIC, Universidad Publica de Navarra – Dept. Telecommunicaciones, Pamplona, Spain: 10/02/2014 – 21/02/2014 and 23/12/2014

1.4.9.2 Scientific missions

• Georgios BIRPOUTSOUKIS
  21/09/2014 24/09/2014 ERNSI 2014, European Research Network on System Identification, Oostende, Belgium. Presentation of poster “A first attempt to optimal experiment design for system identification under regularized parameter estimation”
  12/11/2014 12/11/2014 IAP DYSCO study day, Ghent. Presentation of poster “A first attempt to optimal experiment design for system identification under regularized parameter estimation”

• Matthias CAENEPEEL
  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract “Macromodels for the Design of Microwave Filters”
  05/05/2014 09/05/2014 Attending workshop on microwave filters and multiplexing networks for space communication systems, Universitat Politecnica di Valencia, Spain
  11/05/2014 14/05/2014 Attending 18th IEEE workshop on Signal and Power Integrity (SPI 2014), Ghent, Belgium. Presentation of paper “Macromodeling of narrow-band bandpass filters based on interpolation of coupling matrices”
  01/09/2014 31/10/2014 Université de Nice, France. Research PhD. Cotutelle

• Adam COOMAN
  02/04/2014 04/04/2014 International workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMIC), KULeuven.
  01/06/2014 05/06/2014 2014 International Symposium on Circuits and Systems (ISCAS 2014), Melbourne, Australia. Presentation of paper “Distortion Contribution Analysis by combining the Best Linear Approximation and noise analysis”
  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract “Distortion Contribution Analysis by combining the MIMO BLA and noise analysis”

• Péter Zoltán CSURCSIA

• Alexander DE COCK
  16/05/2014 16/05/2014 IAP DYSCO Study Day Namur. Presentation of poster “A preliminary study on D-Optimal Input Design for Nonlinear Systems”
Introduction to the department ELEC

- Philippe DREESEN
  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Algebraic-Geometric Decoupling of Multivariate Polynomials"
  17/12/2014 17/12/2014 KU Leuven Minisymposium tensors (PhD defence Nick Vannieuwenhoven, Dept. Computer Science), Leuven, Belgium. Presentation “Decoupling multivariate functions using tensor decompositions applied to block-oriented system identification”

- Alireza FAKHRIZADEH ESFAHANI
  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract “Using the best linear approximation with varying excitation signals for nonlinear system characterization”

- Egon GEERARDYN
  16/05/2014 16/05/2014 IAP DISCO Study Day Namur. Presentation of poster “The Local Rational Method for H-infinity Norm Estimation”
  24/08/2014 29/08/2014 19th IFAC World Congress, Cape Town (South Africa). Presentation of paper “Enhancing H-Infinity Norm Estimation using Local LPM/LRM Modeling: Applied to an AVIS”

- Jan GOOS
  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract “Frequency domain LPV state space identification for fast and slow periodic parameter variation”
  04/06/2014 06/06/2014 the American Control Conference, Portland, Oregon (USA). Presentation of paper “Estimation of Linear Parameter-Varying affine state space models using synchronized periodic input and scheduling signals”
  24/08/2014 29/08/2014 19th IFAC World Congress, Cape Town (South Africa). Presentation of paper “Comparative study of two global affine Linear Periodic Parameter Varying State Space model estimation algorithms”
  21/09/2014 24/09/2014 ERNSI 2014, European Research Network on System Identification, Oostende, Belgium. Presentation of poster “Periodic Linear Parameter-Varying identification: state space and input-output models in the frequency domain”
  15/12/2014 17/12/2014 IEEE Conference on Decision and Control (CDC-2014), Los Angeles, USA.

- Gabriel HOLLANDER
  29/06/2014 18/07/2014 Wolfram Science Summer School, Boston, USA.

- Mariya ISHTEVA
  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract “Tensors and structured matrices of low rank”

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Annual report ELEC 2014

19/05/2014  22/05/2014  International Conference on Numerical Methods for Scientific Computations, Bansko, Bulgaria. Lecture "Structured low-rank approximation by factorization"

26/05/2014  27/05/2014  Structured Matrix Days, Université de Limoges. Invited lecture "Structured matrix low-rank approximation and its application for solving tensor problems"


- John LATAIREF

25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands.
16/06/2014  20/06/2014  Lecture at the Summer School on Data-driven Modelling for Control organised bij Dutch institute for Systems and Control (DISC), Zandvoort, The Netherlands.
24/08/2014  29/08/2014  19th IFAC World Congress, Cape Town (South Africa). Presentation of paper "Frequency-domain least-squares support vector machines to deal with correlated errors when identifying linear time-varying systems"
21/09/2014  24/09/2014  ERNSI 2014, European Research Network on System Identification, Oostende, Belgium. Presentation of poster "Regularised system identification, formulated in the frequency domain"

- Vladimir LAZOV


- Ebrahim LOUARROUDI


- Hannes MAES

25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Estimation of respiratory impedance on breathing patients"
16/05/2014  16/05/2014  IAP DYSCO Study Day Namur

- Anna MARCONATO

25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Linking regularization and low-rank approximation for impulse response modeling"
16/05/2014  16/05/2014  IAP DYSCO Study Day Namur. Presentation of poster "Study of the effective number of parameters in nonlinear identification benchmarks"

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Introduction to the department ELEC

24/08/2014  29/08/2014  19th IFAC World Congress, Cape Town (South Africa). Presentation of paper "Linking regularization and low-rank approximation for impulse response modeling"


• Ivan MARKOVSKY

19/05/2014  22/05/2014  International Conference on Numerical Methods for Scientific Computations, Bansko, Bulgaria. Lecture "Data-Driven Signal Processing: A Low-rank approximations approach"

06/06/2014  13/06/2014  The householder Symposium XIX on Numerical Linear Algebra, Spa, Belgium. Presentation of poster "Structured low-rank approximation with missing data"

15/06/2014  20/06/2014  Attending Dobbiaco Summer School on Matrix Theory and Computation with Applications to Network Analysis, Quantum Chemistry and Dynamical Systems, Dobbiaco, Italy.


• MAYANK


• Oscar OLARTE

12/05/2014  15/05/2014  I2MTC 2014, IEEE International Instrumentation and Measurement Technology Conference, Montevideo, Uruguay. Presentation of paper "Glucose Characterization Based on Electrochemical Impedance Spectroscopy"

• Rik PINTELON

18/02/2014  18/02/2014  Seminar at the University of Warwick, School of Engineering "What can System Identification Offer to Impedance Spectroscopy?"

25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands.

16/05/2014  16/05/2014  IAP DYSCO Study Day Namur


• Rishi RELAN

25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Error analysis of discrete-time models without a direct term for Band-Limited measurements"

21/09/2014  24/09/2014  ERNSI 2014, European Research Network on System Identification, Oostende, Belgium. Presentation of poster "Quantifying the error of the discrete-time models with forced delay for band-limited measurements"


• Yves ROLAIN

25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands.

02/04/2014  04/04/2014  International workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMIC), KULeuven.

Annual report ELEC 2014

06/10/2014 09/10/2014 European Microwave Week 2014 (EUMC2014), Rome, Italy

- Johan SCOUKENS

  20/01/2014 21/01/2014 Ecole Central de Lyon, Laboratoire Ampère (CNRS): Member jury Xavier Bombois concernant l'Habilitation à Diriger des Recherches de Xavier Bombois.


  18/02/2014 18/02/2014 Seminar at the University of Warwick, School of Engineering "System identification in a real world"

  14/03/2014 16/03/2014 13th International Workshop on Advanced Motion Control (AMC), Yokohama, Japan. Invited lecture "System Identification in a Real World"

  20/03/2014 20/03/2014 Invited speaker "une journée scientifique à L'Amphi Janet de Supélec, Le laboratoire des signaux et systèmes" on the occasion of the retirement of Éric Walter. "System Identification in a Real World"

  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands.

  16/06/2014 18/06/2014 Lecture at the Summer School on Data-driven Modelling for Control organised bij Dutch institute for Systems and Control (DISC), Zandvoort, The Netherlands.


- Maarten SCOUKENS

  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Modeling a broadband Doherty power amplifier using a parallel Wiener-Hammerstein model!"

  24/08/2014 29/08/2014 19th IFAC World Congress, Cape Town (South Africa). Presentation of paper "Identification of parallel Wiener-Hammerstein systems with a decoupled static nonlinearity"

- Julian STOEV


- Koen TIELS

  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Initial estimates for Wiener-Hammerstein models via basis function expansions"

  16/05/2014 16/05/2014 IAP DYSCO Study Day Namur

  24/08/2014 29/08/2014 19th IFAC World Congress, Cape Town (South Africa). Presentation of paper "Generation of initial estimates for Wiener-Hammerstein models via basis function expansions"

- Diana UGRYUMOVA

  25/03/2014 27/03/2014 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "FRF estimation in the presence of missing output data"

  16/05/2014 16/05/2014 IAP DYSCO Study Day Namur. Presentation of poster "Nonparametric FRF estimation from data with partially missing output"
Introduction to the department ELEC

21/09/2014  24/09/2014  ERNSI 2014, European Research Network on System Identification, Oostende, Belgium. Presentation of poster "Frequency response matrix estimation from partially missing data"

- **David URIBE**

  24/08/2014  27/08/2014  Meeting with Advisor Prof. Wallashchek at University of Hannover, and meeting with Prof. Schmieder at University Hospital Bochum.

  28/08/2014  29/08/2014  Bochum, Germany. Meeting at the neurosurgery clinic, University Hospital Bochum for discussion and preparation of a FWO project proposal.

- **Mark VAES**

  25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Experimental driven demystification of system identification for nonlinear mechanical systems"


- **Leo VAN BIESEN**

  10/04/2014  13/04/2014  Visit ISTIC Université de Rennes, France.

  26/08/2014  28/08/2014  Meeting VIM (International Vocabulary on Metrology), Bureau International de Poids et Mesures, Paris, France


- **Laurent VANBEYLEN**

  01/02/2014  07/02/2014  IMAC XXXIII A Conference and Exposition on Structural Dynamics, Florida, Orlando. Presentation of paper "Nonlinear black-box identification of a mechanical benchmark system"

  25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands. Presentation of paper "Identification of nonlinear dynamic systems: NL-LFR approach, the MIMO case with several nonlinearities"

  24/06/2014  27/06/2014  European Control Conference, Strasbourg, France. Presentation of paper "Identification method for nonlinear LFR block-oriented models with multiple inputs and outputs"


- **Gerd VANDERSTEEN**

  25/03/2014  27/03/2014  33rd Benelux meeting, Heijen, The Netherlands.

  16/05/2014  16/05/2014  IAP DYSCO Study Day Namur

  01/06/2014  05/06/2014  2014 International Symposium on Circuits and Systems (ISCAS 2014), Melbourne, Australia. Tutorial "Nonlinear distortion analysis of circuits and systems"


- **Evi VAN NECHEL**


- **Dieter VERBEKE**

Annual report ELEC 2014

- Maral ZYARI

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>02/04/2014</td>
<td>04/04/2014</td>
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<tr>
<td>25/03/2014</td>
<td>27/03/2014</td>
</tr>
<tr>
<td>21/09/2014</td>
<td>24/09/2014</td>
</tr>
</tbody>
</table>

- International workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMIC), KULeuven.
- 33rd Benelux meeting, Heijen, The Netherlands. Presentation of abstract "Nonlinear RF Measurement and modeling: going beyond the NVNA”
- ERNSI 2014, European Research Network on System Identification, Oostende, Belgium. Presentation of poster “Modelling a mechanical tuner”
1.5 FUNCTIONAL ORGANISATION OF THE DEPT. ELEC

**Head of department ELEC**

J. Schoukens

- **Technical assistance**
  - Electronic Design assistance
    J. Pattyn
    W. Detourte
  - Mechanical Design assistance
    J. Pattyn
  - Didactical Design assistance
    J. Pattyn
  - Purchase Electronic Components
    J. Pattyn
  - Purchase General Components
    J. Pattyn
  - Instrument Maintenance Coord.
    W. Detourte
  - Instrument Inventory & Loan serv.
    W. Detourte
  - Office/ Lab. accommodation
    J. Pattyn

- **Administration**
  - Centralization
  - Correspondence
  - Personnel Files
  - Thesis printouts
  - Administration
  - Purchases
  - Contracts
  - Office material stock
  - General secretariat
  - Accounting
  - B. Huygen
  - A. Pintelon
  - A. Scheyers

- **Infocenter**
  - Instrument and accessory overview
    J. Pattyn
  - Library
  - Magazine overview
  - Literature overview
  - Spare manuals
  - Thesis books
  - Data books
  - Course notes
  - Lab. Notes
  - Internal notes
  - Publication list
  - Annual Report
  - A. Pintelon

- **Education**
  - Courses
    Educational staff
  - Labs and Exercises
    Scientific staff
  - Lab-exercises
    Coordinator
    Gerd Vandersteen
  - Lab assistance
    J. Pattyn

**Research Organization**

- Coordination
  - Thesis/PhD follow-up
  - Industrial contacts
  - Job students follow-up
  - Staff follow-up
  - L. Van Biesen - team A
  - J. Schoukens - team B
  - G. Vandersteen - team C
  - W. Van Moer - team D
  - Research work
  - Research staff

**Support to other bodies, internal or external to the VUB**

- FLAMES: Flanders Training Network for Methodology and Statistics: VUB delegate: Kurt Barbé
- IEEE Instrumentation & Measurement Society, Adcom
  - R. Pintelon, Y. Rolain, G. Vandersteen, W. Van Moer
  - Members: editors
  - Vice President Publications: W. Van Moer
- IEEE Benelux Chapter of the Engineering in Medicine and Biology Society:
  - Member of the steering committee: Kurt Barbé
- IMEKO:
  - L. Van Biesen, President, Liaison Officer to IEEE
  - IMEKO General Council L. Van Biesen, Chairman
  - IMEKO Technical Board: L. Van Biesen, member
  - IMEKO Editorial Board: L. Van Biesen, member
  - IMEKO Advisory Board: L. Van Biesen, member
- ELSEVIER - IMEKO Journal "Measurement":
  - L. Van Biesen, associate editor

**Personnel**

- Job students
- Follow-up
  - Scholarships
  - Research contracts
  - Contract renewal
  - Visiting researchers/professors
  - A. Pintelon

**Public Relations**

- Annual Report
  - Internet - ELEC home page
  - A. Pintelon

**National/international contacts**

- Organisation of workshops, conferences, ... research staff
  - A. Pintelon

**Computer Support**

- PC workstations ELEC
  - Y. Rolain
  - J. Pattyn
  - S. Reyniers

- Support network ELEC
  - Y. Rolain
  - J. Pattyn
  - S. Reyniers

**Introduction to the department ELEC**
1.6 LIST OF THE MOST IMPORTANT MEASUREMENT EQUIPMENT

1.6.1 Signal Generators

- HP E1445A VXI Arbitrary Waveform Generator, fmax < 40 MHz (3x)
- HP E1340A VXI Arbitrary Waveform Generator, fmax < 42 MHz (3x)
- Synthesizer/Function Generator, Agilent 33120A (2x)
- NI 5411 AWG
- Noise Source, HP 346B, 10 MHz-18 GHz
- Agilent, 4142B, DC power supply
- HP E1434A VXI Arbitrary Waveform Generator, 4 channel source, fsmax: 65 KHz
- HP, Signal Generator, HP 83650B, 45 MHz - 40 GHz
- Tektronix, AWG710, 4 GHz
- Tektronix AWG 7052, 5GHz Arbitrary Waveform Generator
- Rhode & Schwarz, Vector Signal Generator, SMIQ06B, 300 kHz - 6.46 GHz
- Agilent 33250A, NI 5411, 2x AWG 33220A
- Agilent 81101A, Pulse generator, 50MHz

1.6.2 Spectrum Analyzers, Impedance Analyzers, Network Analyzers

- 2 channel Dynamic Signal Analyzer, HP 3562, 100 kHz (2x)
- Impedance Analyzer, HP 4192A, 5 Hz - 13 MHz
- Vector Impedance Meter, HP 4193 A, 0.4 - 110 MHz
- Spectrum Analyzer, R&S FSU, 20 Hz- 67 GHz
- µwave Network analyzer, E8364B, 10 MHz - 50 GHz
- µwave Network analyzer, N5242A, 10 MHz – 26.5 GHz 4 port
- Noise Gain Analyzer, Eaton 2075 B, 10 MHz - 1800 MHz
- Network Analyzer, HP 8753 C, 300 kHz - 6 GHz
- Spectrum Analyzer, HP 8565 E, 9 kHz - 50 GHz
- PNA Network Analyzer, Agilent, 5 0MHz - 50 GHz
- Impedance Analyzer, Agilent E4991A, 10MHZ - 3GHz
- Anritsu BTS Master MT8222A, High Performance, Handheld Base Station Analyzer
1.6.3 Digitizers

- 4 channel digitizer, Nicolet 490, 200 MHz, 8/12 bit
- 4 channel Digital Sampling oscilloscope, HP 54120T, 20 GHz, 11 bit
- 1 channel, HP E1430A VXI ADC 10 MHz, 16 bit (10x)
- 1 channel, HP E1437A VXI ADC 20 MHz, 16 bit (4x)
- 2 channel, HP E1429B VXI ADC 20 MHZ, 12 bit (2x)
- 8 channel, HP E1433A VXI ADC 196 KHz
- 2 NI 5911 flexres digitizer
- TDS 3032 digital phosphor oscilloscope, Agilent D5060321 300MHz, TDS 2001C 50 MHz
- 6 NI Elvis II

1.6.4 Miscellaneous

- Dual programmable filter, Difa PDF 3700, 100 kHz
- Dual adjustable filter, Wavetek, 100 kHz
- Logic state analyser HP 1645A
- µwave power meter, HP436A, 10 MHz- 18 GHz
- 4 VXI racks + 4 MXI controllers + Digital cards
  (2x Agilent E4841A + 1 Agilent E4805A)
- HP E1450, VXI timing module
- HP E1446A, VXI power module generator
- Wafer Probe Station
- Polytec Optical Fibre Vibrometer
  Velocity range (Doppler interferometer): 1, 5, 25, 125, 1000 mm/s/V
  Displacement range (Fringe Counter): 2, 8, 20, 80, 320, 1280, 5120 □m/V
- 2 PXI mainframes + MXI controller + embedded controller
- Custom-built measurement setup for making geo-referenced GSM network measurements
- 4 hTC P3600 smart phones (equipped with 2G, 3G, Bluetooth, WiFi and GPS)
- 2 JRC DGPS 200

1.6.5 Underwater Acoustics

- Raytheon V860 echo sounder
B&K hydrophones, amplifiers etc.
Panametrics transducers (500 kHz, 1MHz)
D-GP5 Beacon Receiver KODEN (KBR-90)
1 water tank + positioning system
Anritsu BTS Master MT8222A, High Performance, Handheld Base Station Analyzer

1.7 FINANCIAL SUPPORT 2014

<table>
<thead>
<tr>
<th>Sponsor (project leader)</th>
<th>Duration project</th>
<th>Activity</th>
<th>Approx. amount (in €)</th>
</tr>
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<tbody>
<tr>
<td>BAS12 (L. Van Biesen/R. Pintelon)</td>
<td>2014</td>
<td>Core Funding dept. ELEC</td>
<td>62,651</td>
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<tr>
<td>DWTC 282 (R. Pintelon)</td>
<td>2012-2017</td>
<td>Dynamical systems, control and optimization (DYSCO)</td>
<td>500,000</td>
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<tr>
<td>EU427 (J. Schoukens)</td>
<td>2013-2018</td>
<td>EU Advanced ERC-grant: Data Driven Structured Modelling of Nonlinear Dynamic Systems</td>
<td>2,500,000</td>
</tr>
<tr>
<td>FWOAL599 (R. Pintelon, S. Vanlanduit – VUB/MECH, J. Dirckx, Univ. Antwerpen)</td>
<td>2011-2014</td>
<td>Parametric and non-parametric techniques for modeling complicated time-variant dynamic systems</td>
<td>120,000</td>
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<tr>
<td>FWTM1610 (Y. Rolain)</td>
<td>2011-2014</td>
<td>Bench fee PhD student Maarten Schoukens &quot;Identification of block-oriented models with parallel structures for nonlinear systems&quot;</td>
<td>3,720</td>
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<tr>
<td>FWOAL662 (Clara Ionescu – U-Gent, G. Vandersteen, J. Schoukens)</td>
<td>2013-2016</td>
<td>Detection and validation of variable visco elastic effects in the respiration system.</td>
<td>140,000</td>
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<tr>
<td>FWOAL648 (J. Suykens, J. Schoukens)</td>
<td>2012-2015</td>
<td>Modelling of structured nonlinear dynamic systems using parametric and nonparametric methods</td>
<td>280,000</td>
</tr>
<tr>
<td>FWOAL673 (Y. Rolain, G. Vandersteen, F. Ferranti, L. Knockaert – U-Gent)</td>
<td>2013-2016</td>
<td>Parametrized macro models for linear and nonlinear microwave and RF.</td>
<td>120,000</td>
</tr>
<tr>
<td>FWOAL75B (I.Markovsky, M. Ishteva, Ph. Dreesen, K. Usevich - CNRS, Univ. of Grenoble, J. Schoukens)</td>
<td>2015-2018</td>
<td>Decoupling multivariate polynomials in nonlinear system identification</td>
<td>252,000</td>
</tr>
<tr>
<td>FWTM712 (M. Ishteva)</td>
<td>2014</td>
<td>Structured tensor low-multilinear rank approximation.</td>
<td>4,000</td>
</tr>
<tr>
<td>IWT608 (G. Vandersteen)</td>
<td>2013-2016</td>
<td>Bench fee PhD student Adam Cooman &quot;Study and development of analysis and design techniques in a model-based framework&quot;</td>
<td>7,437</td>
</tr>
</tbody>
</table>

Legal Expertise (L. Van Biesen) | Since 1995 | Expert to the court | Confidential |
License Identification Toolbox (J. Schoukens) | Since 1994 | Identification Toolbox | Confidential |
NDA29 (L. Van Biesen) | Since 2004 | Cellular positioning | Confidential |
1.8 AWARDS

1.8.1 Grade of Fellow (IEEE)

The Institute of Electrical and Electronic Engineers, Inc. elected the grade of fellow to:

- **Michel Gevers**: for contributions to the understanding and identification of linear multivariable systems (1990)
- **Johan Schoukens**: for contributions to frequency domain system identification and the integration of measurement, signal processing and estimation theory (1997)
- **Rik Pintelon**: for fundamental research in frequency domain system identification and its applications in instrumentation, control and signal processing (1998)
- **Yves Rolain**: for contributions to measurement and modeling of nonlinear microwave devices (2005)

1.8.2 Grade of Senior member (IEEE)

- **Leo Van Biesen**: In recognition of professional standing (1990)
- **Gerd Vandersteen**: In recognition of professional standing (2007)
- **Wendy Van Moer**: In recognition of professional standing (2007)
1.8.3 Awards from IEEE Instrumentation and Measurement Society (US)


- **Yves Rolain** received the Recipient of the 2004 IEEE Instrumentation and Measurement Society award “For Contributions to Nonlinear Circuit technology”.

- **Johan Schoukens**: IEEE Society Distinguished Service Award For technical and professional leadership of the IEEE Instrumentation and Measurement Society as Technical Program Co-Chair of IMTC/96 and author of conference papers on an annual basis, Associate Editor of the IEEE Transactions on Instrumentation and Measurement and member of the Society of Administrative Committee

- **Wendy Van Moer** received the “2006 Outstanding Young Engineer Award” from the IEEE Instrumentation and Measurement Society for outstanding contributions to nonlinear circuit theory.

- **Rik Pintelon** received the “2010 TIM Outstanding Associate Editor Recognition” for the meticulous, objective, professional and timely manner by which responsibilities while overseeing the review processes of numerous papers in 2010 are conducted.

- **Wendy Van Moer** received the “TIM Outstanding Associate Editor Recognition” in 2010 and 2011 for important contributions to TIM: for the meticulous, objective, professional and timely manner by which responsibilities while overseeing the review processes of numerous papers in 2010 are conducted.

- **Rik Pintelon** On behalf of the IEEE Transactions on Instrumentation and Measurement (TIM) administrative committee and the Instrumentation and Measurement Society (IMS) Publications Committee sincerely thanks Rik Pintelon for His meticulous, objective, professional and timely manner by which he conducted his responsibilities while overseeing the review processes of numerous papers in 2011. Therefore, we acknowledge your important contributions to TIM by recognizing Rik Pintelon as a 2011 TIM Outstanding Associate Editor.

- **Kurt Barbé** received the “2011 Outstanding Young Engineer Award” from the IEEE Instrumentation and Measurement Society for the innovative application of statistical techniques and signal analysis in biomedical measurements.

- **Lee Gonzales Fuentes** received the IEEE Graduate Fellow” from the IEEE Instrumentation and Measurement Society for her project “Kernel density estimators for the disturbing noise in sampling oscilloscopes”.

- **Kurt Barbé** received the “TIM Outstanding Associate Editor Recognition’ of the IEEE Transactions on Instrumentation and Measurement in 2012

- **Kurt Barbé** received the ‘Best Reviewer Award’ of the IEEE Transactions on Instrumentation and Measurement in 2009 and 2012
• Kurt Barbé received the ‘Andrew R. Chi Best Paper Award 2013’ of the IEEE Transactions on Instrumentation and Measurement for the paper "Analyzing the Windkessel model as a potential candidate for correcting oscillometric blood pressure measurements" by Kurt Barbé, Wendy Van Moer and Danny Schoors.

1.8.4 Award from IEEE Control Systems Society

Michel Gevers: Distinguished Member of the IEEE Control Systems Society in recognition of exceptional service to the Society and the profession (1997)

1.8.5 Grade of Fellow (IFAC)

Michel Gevers: For fundamental contributions to system identification and its connection to control (2006)

1.8.6 Belgian Francqui Chair ULB


Linear models are at the basis of many engineering activities. The aim of this course is to identify these models from experimental data. In real life, nonlinear distortions violate the ideal linear framework. Two solutions are discussed to extend the classic linear modelling approach. First the linear framework will be extended to include these distortions using best linear approximations and nonlinear noise sources. Alternatively, the nonlinear distortions will be explicitly modelled.

Lectures (see pdf-files at http://wwwtw.vub.ac.be/elec/ELECcourse.htm):

• Inaugural: System Identification from data to model
• Lesson 1: Frequency Response Function Measurements
• Lesson 2 : Impact of Nonlinear Distortions on the Linear Framework
• Lesson 3: System Identification (pdf-file)
• Lesson 4 : Identification of Linear Systems
• Lesson 5: Identification of Nonlinear Systems

1.8.7 Awards granted by the VUB, on the proposition of the department ELEC

• Title of Doctor Honoris Causa to Prof. P. Eykhoff (Technische Universiteit Eindhoven) on April 4, 1990 (VUB, Brussels)


**1.8.8 Distinguished Service Award from IMEKO**

The International Measurement Confederation extends to Prof. Leo Van Biesen this Distinguished Service Award:

- As recognition and appreciation for his valuable contribution to the international exchange of scientific and technical information relating to developments in measuring techniques, instrument design and manufacture and in the application of instrumentation in scientific research and in industry.
- For his continuous support in IMEKO as member of several TCs, delegate of the Belgian Member Organization to the General Council, President Elect and Chairman of the Technical Board from 2000 to 2003, President of the Confederation from 2003 to 2006 and Past President and Chairman of the Advisory Board from 2006 to 2009.

**1.8.9 Joseph F. Keithley Award in Instrumentation and Measurement: IEEE Field Award**

Prof. Rik Pintelon received the 2012 Joseph F. Keitley Award in Instrumentation and Measurement, for outstanding contributions in electrical measurements.

Rik Pintelon has played a pioneering role in introducing system identification to the instrumentation and measurement field as a modern approach to solving measurement problems. System identification involves using statistical methods to build mathematical models of dynamical systems using measured data.

Dr. Pintelon's innovative methods have found important use in a diverse range of areas, including measurement and modeling of metal corrosion and deposition, electric machines, inner-ear dynamics, and analysis of civil engineering structures. Dr. Pintelon also developed a frequency domain approach to system identification and pushed for its adoption within the control systems community. In 1991, he and his colleagues were successful in developing the Frequency Domain System Identification...
Introduction to the department ELEC


1.8.10 Doctor Honoris Causa

Prof. Em. Michel Gevers received the title of “Doctor Honoris Causa” from the Vrije Univeristeit Brussel in November 2001 and from the Linköping University (Sweden) in 2010.

Prof. Em. Ronny Van Loon received the title of “Doctor Honoris Causa” from the Hanoi University of Technology, in October 2008, for his personal contributions to the VLIR HUT IUC program in particular and the development of Hanoi University of Technology in general over the past 10 years. Thanks to his tremendous efforts as a key promoter since the establishment in 1998, the VLIR IUC programs with HUT has vigorously developed and reaped fruitful achievements, significantly contributing to the expansion of international network and international academic exchange at Hanoi University of Technology.

Prof. Dr. ir. Johan Schoukens received the title of “Doctor Honoris Causa” from the Budapest University of Technology (Hungary) in May 2011.

1.8.11 Member of the “Royal Flemish Academy of Belgium for Science and the Arts”

Prof. Dr. ir. Johan Schoukens has been elected in December 2009 as member of the “Royal Flemish Academy Of Belgium For Science And The Arts” for the section “Technical Sciences”.

1.8.12 Paper/presentation awards (since 2008)

Carine Neus received at the Symposium on Communications and Vehicular Technology in the Benelux (2008) the “Best Paper Award” for the paper "Challenges for Loop Identification and Capacity Estimation of DSL with Single Ended Line Testing”.

Carine Neus received from IMEKO the “Best Paper Award” for the paper “Feasibility and problems of DSL loop topology identification via single-ended line tests” presented at the 16th IMEKO TC4 International Symposium and 13th International Workshop on ADC Modelling and Testing, Florence, Italy (September 2008)


Mussa Bshara and Leo Van Biesen received the “Top Six Achievement Award “Winning Paper” for the paper "Potential Effects of Power Line Communication on xDSL Inside the Home Environment” presented at the VIII Semetro. 8th International Seminar on Electrical Metrology João Pessoas, Paraíba Brazil June 17 - 19, 2009

Mussa Bshara and Leo Van Biesen received the “Best Paper Award” for the paper “Fingerprinting-based Localization in WiMAX networks depending on SCORE measurements”, presented at the Fifth Advanced International Conference on Telecommunications, AICT 2009, Venice/Mestre, Italy, May 24-28, 2009


Yves Rolain received the “Automated RF techniques group best paper award” from IEEE in 2010

John Lataire received the "Best Junior Presentation Award 2010" at 29th Benelux Meeting on Systems and Control in Heeze, The Netherlands. He received the DISC trophy for the presentation of the paper "Frequency Domain Least Squares Estimator of Time-Varying systems".


Lee Gonzales The journal paper: “Cognitive Radios: Discriminant Analysis for Automatic Signal Detection in Measured Power Spectra” was certified as Finalist for the EMBS Best Paper Award in Transactions Publications by the IEEE Engineering in Medicine and Biology Society Benelux Chapter 2013, in December 5th 2013.


1.8.13 Master thesis awards

Diane De Coster received in October 2011 from FWO the "Barco High Tech Awards for Master thesis", for her master thesis entitled "Ontwerp en realisatie van een geminiaturiseerde elektronische lock-in detectimodule voor het meten van biomoleculen in fotonische 'lab-on-a-chip' systemen".
Maarten Schoukens received in March 2011 from IMEC the “IMEC-award for the best Master thesis at the faculty of Engineering, at the Vrije Universiteit Brussel” for his master thesis entitled “Ontwerp en realisatie van een compensatie voor niet-lineaire RF vermogenversterkers”.

Egon Geerardyn received in March 2012 from IMEC the “IMEC-award for the best Master thesis at the faculty of Engineering, at the Vrije Universiteit Brussel” for his master thesis entitled “A simulation Method for Pin-pointing the Dominant Nonlinear Contributors in CMOS Circuits”.

Adam Cooman received in March 2013 from IMEC the “IMEC-award for the best Master thesis at the faculty of Engineering, at the Vrije Universiteit Brussel” for his master thesis entitled “Design and Analysis of an On-chip Programmable Op-amp Based Filter”.

1.9 INTERNATIONAL/NATIONAL CONFERENCES/WORKSHOPS ORGANISED BY THE DEPT. ELEC

International conferences

- International Instrumentation and Measurement Technology Conference (IMTC), Brussels (Belgium), 4-6 June, 1996
- 16th International IFAC Symposium on System Identification (IFAC-SYSID), Brussels (Belgium), 11-13 July, 2012
- Annual Symposium of the IEEE EMBS and IM Benelux Chapter and National Day on Biomedical Engineering, Brussels, Belgium, 5-6 December 2013

International workshops

- 22nd Benelux meeting on Systems and Control, Vossemereen (Lommel), 19-21 March, 2003
- 26th Benelux meeting on Systems and Control, Vossemereen (Lommel), 13-15 March, 2007
- 30th Benelux meeting on Systems and Control, Vossemereen (Lommel), 15-17 March, 2011
- ERNSI’2014, 21-24 September 2014, Ostend, BELGIUM

National workshop

- IAP DYSCO study day, Palais des Académies, Brussels, November 22, 2013
2. Short Description of the Research Projects

2.1 TELECOMMUNICATION: APPLICATIONS

2.1.1 Development of unified modeling, analysis and design strategy (Model-Aided Engineering) for the compensation of non-idealities within telecom applications

Vladimir Lazov, Gerd Vandersteen

Funding resource: Strategic Research Program (SRP-19) "Center for model-based system improvement: From Computer-Aided Engineering to Model-Aided Engineering"

Various circuit blocks in telecommunication systems such as frequency converters, samplers and oscillators have a periodically time varying nature. Noise generated and processed by them therefore needs to be described using periodically time varying statistics. Possible representations of such noise sources are using cyclostationary noise sources. Additionally, noise performance of various circuits that are part of transmitters and receivers are described with the concept of the noise figure. Noise at the output of the mixer has periodic time-varying statistics and is cyclostationary due to the periodic modulation introduced by the local oscillator [1]. The presence of the cyclostationary noise at its output can be observed by looking at the power spectrum which is not only a function of frequency, but also a function of the time. Therefore, we focus on providing a complete description and characterization of the cyclostationary process when it is processed by linear periodically-time varying (LPTV) system. New method will be proposed how to characterize the cyclostationary processes, extending the already existing algorithms.

The aim is to extend the identification of the LPTV systems using Local Polynomial Method (LPM) by including the cyclostationarity of the noise. The aim of the LPM is to suppress the leakage error by estimating nonparametrically the frequency response function (FRF) and the leakage error over a small frequency range.

A first important practical question is to find and check the assumption under which the cyclostationary process becomes a stationary one. Two examples of converting a cyclostationary process CS(t) into a stationary one y(t) are shown in the Figure 1. Our goal is also to grow the awareness by recognizing and exploiting cyclostationarity in the design process rather than ignoring it by treating signals as if they were stationary.
Short Description of the Research Projects

Figure 1: Left: A cascade of two mixers. Right: A cascade of a mixer and a low pass filter (LPF) and the signals used for both scenarios denoted as: input signals \( x(t) \), output signals \( y(t) \) and cyclostationary signals \( CS(t) \)

Reference:


2.2 SYSTEM IDENTIFICATION AND PARAMETER ESTIMATION OF LINEAR, NONLINEAR AND TIME VARYING SYSTEMS

2.2.1 Development of a user-friendly identification methodology for massive multiple-input-multiple-output systems

Dieter Verbeke, Johan Schoukens

Funding: Flemish Government (Methusalem project)

The goal is to develop a user-friendly methodology to identify systems with a large number of inputs and outputs. Future state-of-the-art mechanical systems such as wafer scanners will have many actuators and sensors (e.g. 30 inputs, 30 outputs). This will increase the need for (semi-) automatic processing of the resulting transfer functions, as the number of FRFs becomes too large to inspect manually.

To deal with this problem, a three-step procedure is envisioned. Step one concerns the acquisition of a high quality nonparametric FRF for each transfer function together with a nonparametric noise model (without user interaction). The local polynomial method (LPM, [1]) and local rational method (LRM, [2]) will play a key role in this part. In step two a parametric model will be identified using one of the classical MIMO approaches. Finally, in step three the models must be validated using the nonparametric information of step one. Those transfer functions that fail the validation test should be further analyzed. It is in this stage that automation will require appropriate validation criteria.

The methods will be theoretically analyzed and verified on experimental setups.

References:


2.2.2 Regularization in FIR estimation: only for short data records?

Anna Marconato, Johan Schoukens

Funding: The Science Foundation Flanders (FWO)

In this work we consider the estimation of the impulse response of a linear dynamic system, based on a set of \( N \) input-output observations. In the last years, the beneficial impact of applying regularization to estimate FIR models has become more and more evident. Although it is commonly believed that the beneficial impact of regularization is mainly present for short data records, in this work we show that this is also the case when a large amount of data is available.

**Regularized FIR models**

In the regularization approach, the cost function is modified to include a penalty term on the model complexity. This has the effect of reducing the variance of the estimate, at the cost of introducing a bias term in the resulting model error.

One can incorporate in the regularization term prior knowledge about the underlying system, so to impose a different complexity penalty for the different parameters. Following the Bayesian approach in [1], it is possible to define a specific covariance matrix (kernel), to include as prior information the smoothness property and the exponential decay of the impulse response.

**Asymptotic performance result**

To study the trend of the performance for the number of estimation data \( N \) growing very large, the ratio between the average mean square error (MSE) values (over 20000 Monte Carlo runs) on a noiseless validation set of the regularized solution and of the least squares estimate is shown (in dB) in Figure 2 for different model orders \( n \). As expected, for short data records the performance gain is evident for all model orders \( n \). However, we observe that, for model orders \( n = 40 \) and \( n = 50 \), the beneficial impact of using regularization does not vanish even for extremely large data sets. For one million data points, the ratio of the validation MSE values is equal to -2 dB for \( n = 50 \), which corresponds to an improvement due to the regularization approach of approximately 20\% in terms of MSE [2]. These remarkable findings has prompted us to investigate the problem more in depth. In [3], theoretical proofs on the asymptotic trend of the regularization performance are derived, explaining the results illustrated above.

![Figure 2: Ratio between the regularization MSE and the least squares MSE (in dB) on a noiseless validation set, in function of the estimation data length \( N \), for different model orders \( n \).](image-url)
2.2.3 Modelling structured dynamical systems: parametric and non-parametric approaches - FWO project 2012 – 2015

Johan Schoukens, Anna Marconato, Johan Suykens*

* Dept. ESAT, Katholieke Universiteit Leuven, Belgium

Funding: The Science Foundation Flanders (FWO)

This FWO project aims at bringing together two modelling paradigms for the study of structured dynamical systems. On one hand, classic system identification, developed within the system and control communities, offers robust methods both in the time and in the frequency domain to model linear and nonlinear systems [1]. On the other hand, support vector machines (SVMs) and kernel methods, originating from the machine learning community, have been extensively studied to solve supervised and unsupervised learning problems and have been successfully employed in a wide range of applications [2].

Objectives

Realizing synergies between these two modelling classes allows one to better understand the strong and weak points of the different approaches from a theoretical point of view, and to propose new methods that integrate the best of two worlds.

Methodology

Two main research directions are considered. First of all, machine learning techniques are employed in the system identification methods as powerful tools to model the nonlinearities in the system. The focus here is on the nonlinear state-space (NLSS) approach, which is well suited to model MIMO systems and for which a separation of the system dynamics and the nonlinear parts is possible [3]. During the identification step, more structure is gradually imposed on the NLSS model, to finally obtain a highly structured representation of the system in a series of successive steps.

A second direction is to extend the (Least Squares)-SVMs methodologies towards the modelling of nonlinear dynamical systems. This includes the study of noise modelling issues, the development of structured kernel based models, the analysis of fixed-size kernel methods and alternative regularization techniques to limit the (potentially high) computational cost.

Within the framework of this project, several topics have been investigated: the notion of effective number of parameters for nonlinear models [4]; the beneficial impact of regularization techniques.
for short and long data records (see topic "Regularization in FIR estimation: only for short data records?" on page 42), and the cost function interpretation of Bayesian regularization approaches (see topic 2.2.4 below).

References


2.2.4 Filter interpretation of the cost function in regularized FIR modeling

Anna Marconato, Johan Schoukens

Funding: The Science Foundation Flanders (FWO)

We consider the estimation of FIR models by means of Bayesian regularization techniques. The regularization approach allows one to obtain solutions characterized by a reduced variance, at the price of slightly increasing the bias term. This is done by embedding in the problem prior information about the underlying linear dynamic system. More specifically, the prior covariance matrix (kernel) of the impulse response of the FIR model is defined to include the assumptions that the impulse response of the system is smooth, and that it exponentially decays to zero. Examples of such matrices are the DC and the TC kernels [1].

A cost function interpretation

In this work, we look at the same problem from a different perspective.

Instead of focusing directly on the kernel matrix, and on how the information about the covariance of the parameters is encoded in such a matrix, we address its inverse, the regularization matrix R,
and we look more closely at how the parameters are penalized through the regularization term in the cost function.

We observe that the inverse R of the (structured) TC kernel (Figure 3a) is a tridiagonal symmetric matrix (Figure 3b), which is derived in closed-form [2]. Inspired by a random walk kernel, we recognize in the cost function, due to the structure of R, a squared differences minimization.

By computing the Cholesky decomposition of R, we obtain a bidiagonal matrix (Figure 3c), also derived analytically. This matrix acts as a prefiltering operation for the parameters, before they enter the cost function. The study of this Cholesky matrix reveals the high-pass nature of the obtained filter, with an increasing gain associated to the parameters at the tail of the impulse response. These results give more insight into the regularized FIR modeling approach, but they also confirm what we already knew about the TC kernel: we aim at constructing a solution which is smooth (i.e. the high frequency components are suppressed), and which decays to zero (i.e. the parameters at the tail are more heavily penalized).

Moreover, this new insight from the cost function perspective could open up possibilities to design the regularization matrix directly, based on the user’s specifications.

References


2.2.5 Full nonparametric identification of linear time-periodic systems

E. Louarroudi, R. Pintelon and J. Lataire

Funding: The Science Foundation Flanders (FWO)

As (quasi) time-periodic (TP) systems are encountered in many engineering applications, ranging from reciprocating devices in the field of mechanics, through harmonic distortions in power distribution networks, to cardio-vascular monitoring in the bio-medical science, the extraction of experimental linear time-periodic (LTP) frequency response function (FRF) models meant for physical interpretation, analysis, prediction or control can be a useful step for the practicing engineer.

Most of the identification methods available in the LTP literature are nonparametric-in-the-dynamics and parametric-in-the-time-variations. Because a full nonparametric model avoids a model order selection for the.

Figure 4 Short-time Fourier Transform (STFT) principle.
dynamics as well as for the time-variation part, it is more than welcome to have full nonparametric identification tools at hand.

Estimation schemes, which are both nonparametric-in-the-dynamics as well as in-the-time-variations, for slowly varying dynamics are based on the short-time Fourier transform (STFT) principle (see Figure 4). However, this can be a very restrictive assumption for applications with fast time-variations. To circumvent this problem, we can show that when the excitation is a stationary random process the identification problem boils down to the estimation of the time-periodic cross power spectral density (PSD) in the extended Wiener-Hopf relation.

\[
\text{time-periodic cross-PSD} = \text{time-periodic FRF} \times \text{input auto-PSD}
\]

As there is quite a lot of research done on how to estimate cyclo-/non-stationary PSDs from noisy data [1], ideas can be used to estimate the time-periodic cross-PSD in LTP systems. For instance, by measuring a sufficient amount of system cycles an unbiased nonparametric estimate can be constructed for the time-periodic cross-PSD through synchronous averaging of the cross-correlation function of the input-output data (see Figure 5).

Reference:


2.2.6 System identification of industrial hydraulic driveline Selecting control friendly nonlinear models

Julian Stoev

This work was supported in part by the Fund for Scientific Research (FWO-Vlaanderen), by the Flemish Government (Methusalem), the Belgian Government through the Inter university Poles of Attraction (IAP VII) Program, and by the ERC advanced grant SNLSID

VUB has extensive experience in identification of experimental systems. It is of particular interest to apply this body of knowledge to diverse relevant industrial cases. FMTC (now Flanders Make) has such experimental setups. The test set-up for this work comprises a hydrostatic drive train as depicted in Figure 6 that is available in the FMTC laboratories.
Nonlinear state-space model of the system

VUB has methodologies to identify the so called PNSS (Polynomial Nonlinear State Space) models - a system composed of a so called best linear approximation (BLA) augmented with multivariable polynomial nonlinearities dependent on the states and the inputs. To do so, a number of experiments were carried out. The goal is to obtain a PNSS model of the hydrostat set-up in the FMTC lab.

Subsystem structure preserving identification

The above experimental setup consists of several hydraulic and electrical subsystems (hydraulic motor, pump, electrical motor,...), each of them with its nonlinearities. It is practically important to preserve the separation of these subsystems and to obtain a model representing each of these subsystems as parts of the bigger model. This is a recent theoretical work performed at VUB and this is an application for this work.

2.2.7 Decoupling Multivariate Nonlinearities in System Identification

Philippe Dreesen, Johan Schoukens

Funding by ERC advanced grant SNLSID

Introduction

Nonlinear system identification often makes use of coupled multiple-input-multiple-output static nonlinear functions to represent nonlinearities [5, 6]. For the sake of model interpretability and to limit the rapid increase of parameters it is desirable to find a parsimonious description. A simplified description may also serve as a good approximation.

We assume that a linear transformation is present at the input as well as at the output, concealing the internal variables between which univariate polynomial mappings exist as in Figure 7.
Figure 7: Decoupling scheme. A given multivariate function $f(u)$ is decoupled into a linear combination of univariate functions in linear forms of the input variables.

First-order Approach

The proposed solution method [2] is based on a first-order information approach. By evaluating the Jacobian of the function $f(u)$ in several operating points, a tensor decomposition [4] problem is obtained from which the unknown linear transformations can be determined, as well as the internal univariate mappings (Figure 7). The canonical polyadic decomposition [4] provides a numerical procedure to determine the unknown linear basis transformations, providing access to the internal variables such that the full structure can be recovered.

Applications

An application to the identification of a parallel Wiener-Hammerstein system was described in [3]. The method can easily be generalized to the question of partially decoupling a given multivariate function in which a ‘block-decoupling’ is obtained. In this case the function $f(u)$ is decoupled in mutually decoupled internal multiple-input-multiple-output nonlinearities in which each has a small number of outputs depending on a small number of inputs. The computational core is in this case the block-term tensor decomposition [1]. Furthermore, a method to unravel the Wiener-Hammerstein structure in a given state-space model is under development which relies on the first-order (full) decoupling approach and linear algebra tools.

Future Work

Several aspects remain to be investigated, such as quantifying approximation errors, understanding how noise influences the estimation of the nonlinear function and under what conditions the linear transformations can be recovered. It will also be investigated how the structure in the problem can be employed to devise tailored algorithms. Finally it will be studied how the structure recovery method can be generalized to other nonlinear block-structures.

References

2.2.8 Extensions of identification methods for nonlinear Linear Fractional Representation models

Laurent Vanbeylen, Anne Van Mulders and Konstantin Usevich

Funding by the Flemish Government (Methusalem) and ERC advanced grant SNLSID

Identification of accurate, parsimonious nonlinear dynamic models is a very challenging research area. Within this field, block-oriented models, consisting of static nonlinear (SNL) and dynamic linear (LTI) blocks, are popular but most of them either lack flexibility (e.g. one-branch open-loop models are usually too simplistic to capture all the effects) or simplicity (e.g. parallel structures, possibly consisting of a large number of parameters and branches, are quite involved). The nonlinear LFR (Linear Fractional Representation) structure (see Figure), is a block-oriented model providing an interesting trade-off between simplicity (parsimony) and flexibility. Indeed, the model has a single SNL, so it is not overly complex. On the other hand, the SNL is surrounded by flexible linear dynamics (MIMO-LTI), which can be compactly described with a linear state-space model. The model automatically accommodates for both nonlinear feedback (which is very important in electronics and mechanical applications; closed loop) and nonlinear feedforward (open loop) effects. Both amplitude-dependent (or operating-point dependent) poles and zeros can be described. If the SNL is Single-Input Single-Output (SISO), the nonlinear LFR model encompasses any block structure with a single SISO SNL and a finite order. As such, the model is well suited to approximate the dominant nonlinear effects in the data and can alternatively be seen as the “first order” correction for a linear model in the nonlinear world, without making specific additional model structure assumptions. The precise location of the SNL need not be known a priori (it automatically follows from the data-driven identification procedure itself) and its input signal need not be measured.

Prior work has been devoted to the development of two approaches:

1. an efficient, user-friendly, iteration-free approach to generate initial estimates and to identify the parameters associated to both blocks, starting from input-output frequency response measurements of the system. The measurements are assumed to generate two different best linear approximations (at least two different classes of input signals are being applied, e.g., by varying the rms-level and/or DC-offset).

2. a structured state-space approach, starting from input-output frequency response measurements (for a single class of inputs). First, a partly structured polynomial (nonlinear) state-space model is estimated, with a nonlinear optimisation. Secondly, an
algebraic approach is used to split the dynamics and the nonlinearities by decomposing the multivariate polynomial coefficients.

The approaches have been extended (under some conditions on the signal dimensions) toward the multivariable case, where the SNL is a MIMO nonlinear mapping and the measured inputs and outputs are multivariable.

References:


2.2.9 Battery modelling project “BATTLE”

Laurent Vanbeylen, Rishi Relan, Yousef Firouz (VUB-ETEC), Johan Schoukens

Funding by the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT639)

This project (BATTery modelling of Lithium chemistries based on an Eclectic approach) addresses the development of a powerful dynamic Li-ion based battery modelling unit for traction applications. This goal can be achieved by developing and combining dedicated models, using innovative numerical simulation and experimental methods and through special validation tools. To accomplish this, a multidisciplinary academic oriented team, extended with an industrial partner has been composed with strong backgrounds in the field of characterizing, modelling, electrochemistry and system identification: VUB-ETEC, VUB-INDI, VUB-SURF, VUB-ELEC, Siemens.

The aim is to increase battery performances (capacity, lifetime, reduction of development costs and of the time dedicated to modelling and testing) by getting improved understanding of the battery at different levels:

- from microscopic (internal behaviour) to macroscopic (external behaviour)
- from short-term to long-term behavior (ageing phenomena)
- different loading conditions, different temperature conditions, different state of charge, different ages
- electrical, electrochemical, electrothermal and thermomechanical fatigue properties of the battery
- statistical cell-dependent manufacturing variations of battery properties.
ELEC contributes to this project by developing and applying linear and nonlinear black-box system identification techniques to model the short-term external electrical battery behavior (input = current, output = voltage). The model could then be used to improve the performance of the battery management system in the vehicle.

Multisine tests have been and are being carried out within VUB-ETEC with two types of high-end battery testers (PEC and BioLogic EIS) under different conditions (state of charge and current amplitude) for a fresh (not aged) high-power 20Ah NMC battery cell at controlled room temperature (in the future other temperatures will be considered). A nonparametric analysis in the frequency domain reveals many phenomena: linear and nonlinear dynamics, thermal and electrical transients (temperature raises slowly before stabilizing), non-idealities of the current source (IGBT’s switching), time-variations and drift (terminal voltage varies during the periods). The measurements reveal dominantly even nonlinearities (-20 dB below signal level) at the lowest state-of-charge values of the battery cell (10%). This is the region where a maximal improvement is expected when switching from linear to nonlinear models (e.g., nonlinear state-space models).

2.2.10 User-friendly identification of massive MIMO systems

Egon Geerardyn, Johan Schoukens, Tom Oomen (TU Eindhoven, the Netherlands)

Funding: the Flemish Government (Methusalem project)

The goal of this project is to develop semi-automatic identification methods that provide a stepping-stone to identify massive multiple-input multiple-output (MIMO) systems, i.e. systems with a very large amount of in- and outputs. As manual tuning becomes intractable to identify such vast systems,
identification methods with limited human interaction are needed. In this project, we focus on the SISO systems, afterwards they will be generalized to the massive MIMO problem.

Experiment design, where classical methods assume the system to be known beforehand, leads to a chicken-and-the-egg problem. Therefore, robust excitation signals and measurement strategies are needed that guarantee a good model quality for a broad class of systems. In this project, quasi-logarithmic multisines were already shown to be an optimal solution [1]. For a specified lower bound on the damping of the system, this allows for a simple but efficient design of the excitation signal.

The Local Rational Method (LRM) [2] has been shown to provide a low-effort non-parametric approach to estimate the system frequency response and model-error $\Delta$. When interpolated, the LRM enhances the estimation of sharp resonance peaks significantly in a measurement time that is almost an order of magnitude shorter than for the Local Polynomial Method (LPM) [4] and methods that rely only on the frequency response function (FRF) on a discrete frequency grid. This is validated on measurements of an industrial active vibration isolation system as shown in the figures.

Current work focuses on the statistical properties of the LRM to provide heuristics that allow to predict at what noise levels and LRM settings, the mean-square-error of the LRM becomes dominated by respectively systematic bias errors or stochastic errors. This provides invaluable information to automatically tune the LRM to obtain improved FRF estimates. Moreover, improved FRFs enhance initial parametric estimates. Consequently, it becomes more likely to obtain good parametric models without any additional user interaction.

References


2.2.11 Initial estimates for Wiener-Hammerstein models using phase-coupled multisines

Koen Tiels, Maarten Schoukens, Johan Schoukens

Funding: EU Advanced ERC-Grant (EU427) and by the Federal Government (Interuniversity Poles of Attraction, IAP VII – DYSCO "Dynamical systems, control and optimization")

Although all physical dynamical systems behave nonlinearly to some extent, linear models are often used to describe them. If the nonlinear distortions become too large, however, a linear model is insufficient, and a nonlinear model is required. One possibility is to use a block-oriented model. Block-
oriented models consist of linear dynamic (L) and nonlinear static (N) sub-blocks. Due to this highly structured nature, block-oriented models offer insight about the system to the user.

We consider the generation of initial estimates for the linear dynamic blocks in a Wiener-Hammerstein model (LNL cascade, Figure 9). While it is easy to measure the product of the two linear dynamic blocks using the best linear approximation (BLA) for a Gaussian excitation, it turns out to be more difficult to split these global dynamics over the individual blocks.

![Figure 9: A Wiener-Hammerstein system consists of a nonlinear static system f sandwiched in between two linear dynamic systems R and S.](image)

In [1], we propose a well-designed multisine excitation with pairwise coupled random phases. Next, we estimate a modified BLA on a shifted frequency grid. It is shown that the input dynamics shift over a user-specified frequency offset \( s \) (in frequency bins), while the output dynamics remain fixed (see Figure 10). The transfer function of the shifted BLA, which has complex coefficients due to the frequency shift, is estimated with a modified frequency domain estimation method. The identified poles and zeros can be assigned to either the input or output dynamics, depending on whether they shift or remain fixed. The method is generalized in [2] from a cubic nonlinearity to a polynomial nonlinearity of arbitrary degree, and the method is illustrated on experimental data obtained from the Wiener-Hammerstein benchmark system [3].

![Figure 10: The BLA of a Wiener-Hammerstein system excited by a Gaussian input is proportional to the product of the two linear dynamic blocks. When using the proposed phase-coupled multisine excitation, the input dynamics shift over a user-specified frequency offset \( s \) (in frequency bins), while the output dynamics remain fixed.](image)

References


2.2.12 Identification of Nonparametric Models for Nonlinear Systems

Georgios Birkoutsoukis, Johan Schoukens

Funding: EU Advanced ERC-Grant (EU427)

Goal

This project aims at the development of efficient methods for the identification of nonparametric Volterra models, which exploit prior information about the system dynamics to be modeled.

Motivation of this study

Modeling the behavior of nonlinear systems constitutes one of the most interesting and challenging topics in the field of System Identification. The reason lies in the fact that the reality around us is nonlinear and complexity is the main characteristic of this behavior. A significant step during the modeling procedure of a nonlinear system is the choice of the model structure. This decision step can be bypassed by considering a nonparametric structure, complex enough to capture the dynamics of the system under study. However, it holds quite often that the size of these models needs to be very large in order to ensure efficient model performance. Accuracy and efficiency in case of a large model is directly related to long data records needed to be measured from the true process. As a consequence, the measurement procedure will take a long time (if possible) and moreover, the processing of long data records requires adequate technological equipment and background to make the model construction fast and user friendly. As a result, new methods need to be developed which will deal efficiently with the aforementioned challenges of the nonparametric representations.

Methodology

In terms of this work the efficiency of regularization methods, that have been successfully applied to estimation of linear models, is investigated for the case of describing a nonlinear process. Inserting prior knowledge about the system under study during the identification step constitutes the core of
this method. In this way, the estimated model is not only based on the current measurements obtained from the process, but also on the information we have a priori about the response of the system. In our case two basic properties of the nonlinear systems under study, namely the stability as well as the smoothness of their response, is injected in the estimation step. Results based on simulations indicate that the method is very promising. The regularization method for nonparametric representations of nonlinear systems will be tested on true nonlinear systems with different behavior.

2.2.13 Measuring nonlinear distortions: from test case to an F-16 Fighter

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Funded by the Flemish Government (Methusalem project)

Introduction

What are the similarities and differences between the behavior of a small vibrating test system and an F-16 fighter? To find it out, we compare measurements of the test system to measurements from the bolted connection of the wing and the missile of a F-16 Fighter Falcon from the Belgian air force. These measurements were done during a ground vehicle test (GVT) campaign. Essentially, the behavior of these systems match, even though the test system is only the heart of a self-study kit for nonlinear system identification and the F-16 is a complex real life mechanical structure. This clearly shows the added value of an experiment driven nonlinear educational system identification package. It provides safe small-scale toy examples for hands-on excersises that react like real systems. We believe that this practical approach lowers the gap between learning system identification concepts and applying it on real systems.

Methodology

The mechanical systems are first excited by a multisine signal with a low measured amplitude. The frequency response function (FRF) is a rather smooth curve with resonance frequencies. When the amplitude is slightly increased, the FRF does not change. The system behaves like a typical linear
time invariant (LTI) system (Figure 12, dark grey). Increasing the amplitude of the input signal further makes the FRF depart from this value for both systems as the nonlinear distortions pop up.

In Figure 12 the resonance frequency of the FRF is shifting to the left for both systems. This shows a softening effect. Note also the increased noise and amplitude change.

Adapting the input signal empowers detection, quantification, and qualification of nonlinear distortions and the measurement noise. What is the gain? Interpretation of these FRF’s leads to a better understanding of both systems and can be of great importance for the practitioner. Odd nonlinear distortion can be detected which lies at the origin of the changes in both dynamics of the system (Figure 13).

Figure 13: Detect, quantify and qualify nonlinear distortions of an F-16 Fighter: black: FRF, blue: even NL, red: odd NL, Green:noise

An example where this knowledge is of great importance is in the case of GVT campaigns. In GVT mostly, LTI-based methods are used to identify the resonance frequencies and predict flutter of an aircraft. If the system contains odd nonlinear distortions, this becomes very dangerous to assess dampings as the dynamics of the system is changed.

An F-16 and the test system look pretty much alike indeed, the kit prepares practitioners to tackle real-world problems.

References:


2.2.14 Design of excitations for structure discrimination of nonlinear systems, using the best linear approximation system characterization

Alireza Fakhrizadeh Esfahani, Johan Schoukens, Laurent Vanbeylen

The project is funded by the EU Advanced ERC-grant: Data Driven Structured Modelling of Nonlinear Dynamic Systems

Introduction

Block-oriented nonlinear models are very popular, since they are composed of well-understood elements, namely linear dynamic parts and static nonlinearities. However, the identification problem of most types of block-oriented nonlinear models can be very difficult (especially the generation of
initial estimates) and time-consuming. Therefore it is of crucial importance to select the most appropriate model structure directly from the measurement data, before proceeding with the actual nonlinear identification. For initializing the structure detecting algorithms it is needed to have a good quality frequency response function (FRF). A method is proposed to have an FRF with minimum distortion level. This method is applied on Silverbox (Figure 14).

**Methodology**

The BLA is defined as the linear system $\mathcal{G}_{BLA}$ that minimizes the mean-square output error [2]. Using the fast or robust method [1], [2], $\mathcal{G}_{BLA}$ and the nonlinear distortions are measured at different amplitudes and DC levels. Using the fast or the robust method [2], $\mathcal{G}_{BLA}$ is measured together with the analysis of the nonlinear distortions. The variability of the BLA measurement will depend on the choice how to vary the excitation signal. We will show that varying the DC level can result in small uncertainties on $\mathcal{G}_{BLA}$, and hence it might be easier to analyze the model structure of the NL system by making this choice. Both approaches (amplitude and DC level variations) are combined, and an excitation strategy is proposed. This strategy has a minimum level of distortion.
Figure 15 BLAs of Silverbox system with different experiments' strategy. Top left: Varying DC level of the input signal. Top right: Varying the STD level of the input signal. Bottom: BLAs of the proposed experiment strategy. BLAs $\theta_{BLA}$ are in black, total distortions are in light grey $\sigma_{total}$, NL distortions $\sigma_{nl}$ are in medium grey, and the noise distortions $\sigma_{noise}$ are in dark grey.

Results

In Figure 15 BLAs of the Silverbox system with DC varying strategy is shown, while in the right side of this figure the BLAs are plotted according to varying STD level of the excitation. The NL distortion is increased by increasing the STD level of the input signal. By combining these two strategies we have the proposed experiments that its results are plotted in the bottom of Figure 15. It is seen that by this experiment, the total distortion level is reduced by 9dB in the resonance region. And the NL distortion reduction is even more.

References

2.3 IDENTIFICATION OF TIME-AND PARAMETER-VARYING SYSTEMS

2.3.1 Estimation of Linear Periodic Parameter-Varying State Space Models

Jan Goos, John Lataire & Rik Pintelon

Funding: the Science Foundation Flanders (FWO)

Although many real systems can be represented very well by a Linear Time-Invariant (LTI) model, in quite some applications the linearity and time-invariance hypotheses are only approximately true or not valid at all. The need to operate processes with higher accuracy and efficiency has, therefore, resulted in the observation that the non-linear (NL) and time-varying (TV) nature of many physical systems must be handled by the control design.

An illustrative example of a time-varying (or time variant) system is an oscillating pendulum, whose rope length is varying. That length directly influences the poles of the system, thereby determining its resonance frequency. In the linear parameter varying (LPV) framework, we call variables such as the rope length scheduling parameters. The dynamic relation between input and output is still linear, but it is continuously adapted based on the trajectory of the scheduling parameters.

During the past decades some very interesting results have been obtained in controller synthesis using Linear Parameter-Varying (LPV) systems. However, the LPV models are commonly required to be transformed into State Space (SS) form. We therefore tackle the LPV SS identification problem directly in the frequency domain.

It is important to note that when the scheduling is chosen to be periodic, the state space equations are structured and sparse in the frequency domain.

Performing the identification in the frequency domain has several other advantages: we can easily select the frequency band of interest and, under mild conditions, we can estimate a non-parametric noise model in a pre-processing step.
The parameters of these state space equations are estimated by minimizing a weighted non-linear least squares criterion in the frequency domain. Starting values are generated via the Best Linear Time-Invariant (BLTI) approximation. The resulting model is also valid for non-periodic scheduling and input signals.

### 2.3.2 Comparative study of two global affine Linear Periodic Parameter Varying State Space model estimation algorithms

#### Jan Goos & Rik Pintelon

**Funding: the Science Foundation Flanders (FWO)**

We compared two state-of-the-art LPV SS identification methods; a time domain LPV subspace identification scheme of [1], called periodic-MOESP, versus a newly developed frequency domain approach [2]. In addition to a theoretical analysis, the performance of the estimates is compared on the simulated flapping dynamics of a wind turbine [1]. For identical experimental conditions 1000 Monte Carlo simulations were carried out. Overall, the frequency domain approach seems to perform better. We compared both methods by means of the Variance Accounted For (VAF), and the invariant eigenvalues of the identified matrices, as proposed in [1].

![Figure 16: VAF time domain](image1.png) ![Figure 17: VAF frequency domain](image2.png)

It can be seen from Figure 16 and Figure 17 that the time domain method has a wider spread on the output error. The mean VAF for the frequency domain is 99.998% with a standard deviation of 0.0016%. In Figure 18 and Figure 19, the invariant eigenvalues of the identified models are shown. The black crosses denote the true values. Again, we find that the frequency domain method has a smaller variance.

Finally, we show that the frequency domain approach reaches the Cramér-Rao lower bound. Figure 20 is a zoomed version of the left upper part of Figure 19. We added the 95% confidence ellipse in red, given the true added noise. 93.7% of the frequency domain estimates fall within this 95% confidence bound. We can therefore conclude that the newly proposed method is not only consistent, but also asymptotically efficient.
Short Description of the Research Projects

Figure 18: estimated eigenvalues time domain method

Figure 19: estimated eigenvalues frequency domain method

Figure 20: 95% confidence Cramér-Rao uncertainty ellipse of the frequency domain estimates. 6.7% of the estimated eigenvalues are outside of the 95% confidence bound

References


2.3.3 Frequency-domain Identification of Time-Varying Systems for Analysis and Prediction of Aeroelastic Flutter

*J. Ertveldt, J. Lataire, R. Pintelon and S. Vanlanduit*

*Funding: the Science Foundation Flanders (FWO project G000211N), the Flemish Government (Methusalem project), and the Federal Government (Interuniversity Poles of Attraction, IAP VII, DYSCO).*

In this project a different approach to wind tunnel flutter testing is presented. This procedure can now be performed as one continuous test, resulting in a major time saving (see Figure 21, the wind velocity increases linearly with time). Both analysis of the current behaviour of the structure, and prediction towards higher velocities, are important for flight flutter testing, and are dealt with in this project. The recently developed time-varying weighted non-linear least-squares estimator (TV-
WNLS) (Lataire and Pintelon, 2011) is applied to the aeroelastic flutter problem. Smooth variation of the transfer function coefficients is forced through the TV-WNLS estimator, and the obtained polynomials are used as basis for predicting the damping ratio towards higher velocities. Selection of the model order is based on linear variation of the airspeed and the evaluation of Theodorsen's unsteady aerodynamics for the frozen time-varying aeroelastic system at a certain constant velocity. Therefore, providing a physical justification for the extrapolation of the damping ratio towards higher velocities. The method is applied to wind-tunnel measurements on a cantilevered wing. It is shown that the proposed method outperforms flutter speed prediction by classic damping ratio extrapolation and a non-parametric analysis of the time-varying signal.

Figure 22 compares the results of the time-invariant measurements (classical approach where the wind velocity is kept constant) to those of the time-variant measurements (new approach where the wind velocity increases linearly with time, see Figure 21). It can be seen that the proposed TV-WNLS estimate outperforms (smaller variability) the short-time maximum likelihood estimate (MLE) of the time-variant measurements and the MLE of the time-invariant measurements.

References

2.3.4 LPV state space identification via the modeling of time-varying differential equations

Jan Goos, Ebrahim Louarroudi & Rik Pintelon

Funding: the Science Foundation Flanders (FWO)

In previous work [1], we proposed a non-linear optimization routine for the identification of LPV state space models. Originally, this method is initialized with the Best Linear Time-Invariant (BLTI) approximation. This approach, depicted in Figure 23) works fine if the parameter variation is slow.

For faster scheduling trajectories however, an LTI approximation can be quite poor. We therefore explore an alternative options, by building on the existing work in our group on time-varying modeling. More specifically, the identification method [2] is used to estimate a time-varying differential equation.

The interesting advantage of this detour is that the identified coefficients can be plotted against the applied trajectory for the external scheduling signal $p(t)$. This way, one can get an idea of the required complexity for the mapping from $p(t)$ to the coefficients of the differential equation. For example, Figure 24 shows the behavior of the coefficients of a third order band-pass filter.

![Figure 23: original LPV identification routine, starting from the BLTI approximation](image)

![Figure 24: coefficients of a third order band-pass filter. The dynamics are most pronounced in $b_1(p(t))$, but still negligible. There is also a hint of non-linearity.](image)
In future research, we will look into a criterion to decide whether or not a static relation is enough to obtain a good model. Note that the obtained model is best used for the excited frequency bands of both the input and the scheduling signals.

As an additional result, we have proven that an arbitrary continuous time-varying SISO differential equation can be transformed into a minimal state space representation. Similar results were already obtained for the discrete time case \[3\]. The drawback is that this transformation introduces dynamic dependence on the scheduling signal \(p(t)\). Nevertheless, we end up with a canonical LPV state space model, which can be used as an initial estimate.

In conclusion, we looked into a new robust, data-driven method to obtain initial estimates for the coefficient functions of a periodic LPV state space model. In a final step, the model complexity can be reduced (at a cost of an increased output error) by pruning dynamic mappings.

References


2.3.5 Nonparametric time-variant frequency response function estimates using arbitrary excitations

\textit{R. Pintelon, E. Louarroudi, and J. Lataire}

\textit{Funding: the Science Foundation Flanders (FWO project G000211N), the Flemish Government (Methusalem project), and the Federal Government (Interuniversity Poles of Attraction, IAP VII, DYSCO).}

The time-variant frequency response function (TV-FRF) uniquely characterizes the dynamic behaviour of a linear time-variant (LTV) system. In this project a method is proposed for estimating nonparametrically the dynamic part of the TV-FRF from known input, noisy output observations. The arbitrary time-variation of the TV-FRF is modelled by Legendre polynomials. In opposition to existing solutions, the proposed method is applicable to arbitrary inputs.

The approach is illustrated on the time-variant electronic circuit shown in Figure 25. Starting from known input, noisy output observations, the TV-FRF \(G(j\omega_k,t)\) is estimated (see Figure 26). As expected, it can be seen from the bottom row of Figure 26 that the time-dependency of the resonance frequency (the largest amplitude in the time-frequency plot) has the same shape as the gate voltage \(p(t)\).
Short Description of the Research Projects

Figure 25: Second order bandpass filter with time-varying resonance frequency and damping ratio. The electronic circuit with input $u(t)$ and output $y(t)$ consists of a high gain operational amplifier (CA741CE), a JFET transistor (BF245B) with gate voltage $p(t)$; three resistors ($R_1 = R_2 = 10 \, k\Omega$ and $R_3 = 470 \, k\Omega$), and two capacitors ($C_1 = C_2 = 10 \, nF$).

Figure 26: Estimated TV-FRF $G(j\omega_k, t)$ of the electronic circuit. Top left: amplitude (red) and variance (blue) of $G(j\omega_k, t)$; top right: phase of $G(j\omega_k, t)$; bottom left: time-frequency plot of $|G(j\omega_k, t)|$; and bottom right: gate voltage $p(t)$.

Reference

2.3.6 Transfer function estimation with Kernel Based Regression

John Lataire, in collaboration with Tianshi Chen (Dept. of Electrical Engineering Linköping University, Sweden)


Kernels for dynamic systems

The transfer function is the most convenient way to represent the dynamics of a linear system. In this work, transfer functions are estimated with tools from the Bayesian framework. Namely, Kernel Based Regression is used, with kernels that have been specifically designed for linear dynamic systems.

Kernels for the estimation of dynamic systems have been introduced in earlier literature [1]. These constrain the estimated system to have an exponentially decaying impulse response, as one expects from a stable system. Also, they impose some smoothness on the impulse response, via a correlation criterion.

Frequency domain kernels

The importance of this work is to provide a frequency-domain interpretation of the existing kernels. This will be explained via Figure 27. The left column gives a graphical representation of the time domain kernel, denoted the DC (Diagonal Correlated) kernel in [1]. The main diagonal of this kernel is exponentially decaying, which enforces the estimated impulse response to be exponentially decaying as well. However, the associated decay rate can be tuned, such as to match that of the system, which would give a good estimate.

A frequency domain interpretation of the tuning of the decay rate is as follows. A slow decay (small decay rate, top left plot) gives a frequency domain kernel (top middle plot) which is mainly significant on the main diagonal. The off-diagonal elements decay very rapidly, which means that the resulting estimated transfer function (blue line in top right plot) is allowed to be non-smooth. The error on the estimate (black dots) is fairly high. This error is mainly due to a high variance.

At the other extreme (bottom figures), a fast decay (high decay rate) gives a frequency domain kernel where the off-diagonal elements are highly significant as well. This yields a smooth estimate of the transfer function. In fact, for this decay rate, the estimated transfer function is so smooth that the bias error is very high.

Figure 27: Left column: time domain kernel, middle column: corresponding frequency domain kernel, and right column: resulting estimated transfer function (blue full line) and error (black dots). These are given for different values of the decay rate of the kernel, providing us with a convenient way to tune the model complexity.
As can be expected, the optimal decay rate is somewhere in between, in the plots in the middle row. A medium decay rate gives an optimal value for the bias-variance trade-off.

Another way of seeing this, is that the model complexity (embodied as the decay rate in this case) should be tuned in such a way as to be able to capture most features of the system at hand, without being too complex. Kernel based regression provides tools to do such model complexity selection in a convenient fashion.

Reference:


2.4 EXPERIMENT DESIGN

2.4.1 Optimizing inputs for Nonlinear Systems with Infinite Memory in the Time Domain

Alexander De Cock and Johan Schoukens

Funding: EU Advanced ERC-Grant (EU427)

Introduction

The quality of system models obtained through identification largely depends on the experimental conditions under which the measurement data was obtained. Therefore experimental design is an important step in the identification process.

One aspect of the experiment that can be optimized is the input signal that is used to excite the system. For linear dynamic systems and nonlinear static systems the problem of optimal input design is well understood and well covered in literature. However, no general solution is known for nonlinear dynamical systems [1].

Problem Statement

Instead of considering the whole class of nonlinear systems, we will limit ourselves to Wiener systems consisting of an Infinite impulse response filter followed by a static differentiable nonlinearity. Notice that this is a subclass of the nonlinear infinite memory systems.

![Figure 28: IIR filter followed by a polynomial nonlinearity](image)

It will be assumed that only the output measurements are corrupted by noise and this noise is Gaussian white independently distributed. The class of inputs will be restricted to multisine excitations and the effect of transient will be neglected (we assume steady state measurements).
Solution Method

Our goal is to obtain a better understanding of what makes an input informative in the case of nonlinear infinite memory systems. However, unlike linear dynamic systems or nonlinear finite memory systems, no global (convex) solver can easily be found. Therefore, a brute force optimization will be performed where we optimize the time samples of the input with the help of numerical nonlinear solvers.

In order to avoid local maxima, the settings of the optimization problem need to be carefully chosen. Three important settings will be considered: the total signal length, the sampling frequency and the initial values of the optimization.

Once the correct settings are known, different systems for the system class will be considered and their optimal inputs designs will be compared in order to detect which aspects of the design influence the information content.

Revisiting The Linear Case

To obtain an insight in how to choose the settings of the problem, we will revisit the linear case. It should be noted that for linear systems, the direct optimization of the time samples is not very common due to the existence of convex optimization methods in the frequency domain. Therefore, investigating the behavior of nonlinear optimization methods in the time domain for linear systems has its own scientific merits.

Results

Successful optimization of the input samples for linear systems has been performed in the time domain with performance comparable to the state of the art designs obtained with the existing convex optimization methods.

Rules of thumbs have been derived for the choice of the signal length and sampling frequency based on the behavior of a second order system. These preliminary results for linear systems where presented on ERNSI-2014, September 21-24, Ostend, Belgium.

Extensions of these rules to the nonlinear case are still in progress and will be presented on the 34nd Benelux Meeting 2015.

Reference

2.5 TIME AND FREQUENCY DOMAIN SYSTEM IDENTIFICATION

2.5.1 Multivariate frequency response estimation from partially missing data for arbitrary inputs

Diana Ugryumova, Rik Pintelon, Gerd Vandersteen

Funding: The Science Foundation Flanders (FWO) & Center for model-based system improvement - From Computer-Aided Engineering to Model-Aided Engineering (SRP19)

Nonparametric Frequency Response Matrix (FRM) estimation is an important preprocessing step in system identification. It needs fewer assumptions than the parametric estimation and quickly provides useful information about the considered dynamic system. The major challenge in the FRM estimation is the reduction of the leakage errors, or the transient effect, which originate from the difference between the initial and final conditions of the experiment. The following is based on the Local Polynomial Method (LPM) that suppresses the leakage errors by estimating the FRM and the leakage errors locally over a small frequency range [1].

Here we tackle the FRM estimation problem when output data is missing, which can happen due to sensor failures or faulty communication links. To overcome this, we split the outputs into two contributions: the outputs discrete Fourier transform (DFT) with all missing samples set to zero and a DFT of the missing output samples. Then, we extend the LPM by putting the missing samples as unknown global parameters. No particular pattern or statistical characteristics of the missing data are assumed. The extension of LPM is made for a multiple-input-multiple-output system with arbitrary noiseless inputs and data missing at the noisy outputs. The new method can simultaneously estimate the FRM, the transient, the missing samples, and their uncertainties. If the reference signal is known, this method can also handle missing data at the noisy inputs (errors-in-variables) and in the presence of a feedback loop.

![Graph](image)

Figure 29: Results are shown from input 1 to output 1. Left: full data FRF estimate (solid black) and its standard deviation (gray) and the bias error due to missing data (dashed black). Right: estimated FRF stds using full data (black) and using partially missing data (gray) are almost identical.

The method has been successfully tested using measurements of a 2x2 mechanical system with mild nonlinearities present. The FRM estimate using the full data is compared with the FRM estimate when a block of 10% is missing at the noisy inputs and outputs, with the reference signals provided.
2.5.2 Time Domain Identification of Linear Time Varying Systems using B-Splines and Regularization

Péter Zoltán Csurcsia, Johan Schoukens

Funding: Flemish Government (Methusalem)

Introduction

The aim of this work is to develop a nonparametric time domain identification method for linear slowly time-variant systems. The proposed methods use a two dimensional impulse response representation. Unlike the linear time invariant systems where the impulse response function is unique, the time varying impulse response is not restricted to only one solution. Assume that the length of input and output is $N$, then the possible variations for the impulse response function are $N^2$. Hence there is no unique impulse response function that relates the input to the output, because there are only $N$ linear relations for $N^2$ unknowns. The user can impose additional constrains to decrease this freedom, for instance smoothness and/or exponentially decaying along the impulse responses. Two methods have been done during the last year.

First, a generalized smoothing spline is used once over the system time (direction of the impulse responses, referring to the behavior) and once over the global time (referring to the system memory). The excess degrees of freedom are removed using a generalized B-spline smoothing technique [1][3].

Second, the key idea of the regularization technique is that by using the prior knowledge (e.g. smoothness) and allowing some bias error, the variance can be significantly reduced resulting eventually in a reduced RMS error [5][6]. This can be done by introducing an additional term in the

References:

least squares minimization criterion that penalizes the model flexibility. In this particular case two-dimensional regularization is used.

An example

In this Section a real measurement example is observed. A second order slowly time varying band-pass filter is examined with sampling frequency (denoted by $f_s$) of 625 kHz. The total length of the measurement consists of 62520 samples. The filter is excited by a frequency limited odd random phase multisine [2]. The input and output signals are band limited.

A frequency domain representation of the filter is shown in Figure 30. Figure 31. shows the results of this methods compared with the frequency domain approach using FDTVident toolbox [4]. This comparison is also made for the ordinary least squares estimation [6] considering that the underlying system is LTI (the selected model order is $L=200$). This can give an idea about what happens if the time variations are not taken into account

Summary

In this work a powerful time domain estimation methods are developed for smooth LTV systems.

This technique is illustrative, flexible, user friendly. With respect to the system dynamics using the proposed methods, it is possible 1) to reduce the model order 2) to decrease the effect of the disturbing noise and 3) to eliminate the transient.

References

2.6 STRUCTURED LOW-RANK APPROXIMATION

2.6.1 Low-rank approximations of tensors via structured matrix methods

Mariya Ishteva, Ivan Markovsky

The project is funded by:
- FWOTM712 "Structured tensor low-multilinear rank approximation" and
- EU414 "SLRA - Structured low-rank approximation: Theory, Algorithms and Applications"

Introduction:
We study a new connection between higher-order tensors and affinely structured matrices, in the context of low-rank approximation. In particular, we reformulate the tensor low multilinear rank approximation problem as a structured matrix low-rank approximation, the latter being an extensively studied and well understood problem.

The symmetric problem:
Although the symmetric tensor problem is at least as difficult as the general unstructured tensor problem, the symmetry allows us to simplify and clearly show the relation to structured matrices.

The tensor low multilinear rank approximation problem can then be easily reformulated as a matrix structured low-rank approximation problem, which can be solved by existing local optimization techniques.

Generalizations:
By imposing linear equality constraints in the optimization problem, the proposed approach is applicable to unstructured tensors, as well as to affinely structured tensors. Therefore, it can be used to find (locally) optimal low multilinear rank approximation with a predefined structure.
Advantages and disadvantages:
An advantage of the proposed approach is that it can deal with more difficult variations of the main problem, including having missing and fixed elements in the given tensor or approximating with respect to a weighted norm. The drawback is its higher computational cost, compared to existing algorithms, partially due to the generality of the approach.

Reference:

2.6.2 Identification of linear time-invariant systems from multiple experiments
I. Markovsky and R. Pintelon
Funded by EU414 "SLRA - Structured low-rank approximation: Theory, Algorithms and Applications"
A standard assumption for consistent estimation in the errors-in-variables setting is persistency of excitation of the noise free input signal. We relax this assumption by considering data from multiple experiments. Consistency is obtained asymptotically as the number of experiments tends to infinity. The main theoretical and algorithmic difficulties are related to the growing number of to-be-estimated initial conditions. A method based on analytic elimination of the initial conditions and optimization over the remaining parameters is proposed and implemented. The resulting estimator is consistent, however, achieving asymptotic efficiency remains an open problem.

References:

2.6.3 Computing the distance to uncontrollability
N. Guglielmi (University of L’Aquila, Italy) and I. Markovsky
Funded by EU414 "SLRA - Structured low-rank approximation: Theory, Algorithms and Applications"
The problem of computing the distance from a given linear time-invariant system to the nearest uncontrollable system is posed and solved in the behavioral setting. In the case of a system with two external variables, the problem is restated as a Sylvester structured distance to singularity problem. The structured distance to singularity problem is then solved by integrating a system of ordinary differential equations which describes the gradient associated to the cost functional. An advantage of the method with respect to other approaches is in its capability to include further constraints. Numerical simulations also show that the method is more robust to the initial approximation than the Newton-type methods.
2.7 MODELLING HIGH FREQUENCY NONLINEAR SYSTEMS

2.7.1 Modeling a broadband Doherty power amplifier using a parallel Wiener-Hammerstein model

M. Schoukens¹, M. Özen², C. Fager², M. Thorsell², G. Vandersteen¹, Y. Rolain¹

(1) Dept. ELEC, Vrije Universiteit Brussel, Brussels, Belgium
(2) Microwave Electronics Laboratory, Chalmers University of Technology, Göteborg, Sweden

Funding: the Science Foundation Flanders (FWO)

Microwave Doherty power amplifiers exhibit some nonlinear distortion behaviour. We propose to use a parallel Wiener-Hammerstein model [1] (see Figure 32) to explain the in-band and spectral regrowth nonlinear effects that are present in the output of the system. The model is compared with some state of the art modeling techniques [2] on measured data.

Data and results

The system is excited using a band pass random phase multitone signals around 3.45 GHz with a bandwidth of 300 MHz. The signals are measured with an oscilloscope. The measured data is downconverted around DC in a post processing step. This results in an asymmetric frequency spectrum, and a complex time-domain signal. Because the measurement setup introduces some delay between the measured input and output, the signals are aligned to remove the delay between the input and output signal. The identification algorithm presented in [1] was enhanced to cope with these difficulties.

The identified model predicts the output well, as is shown in Figure 33. The model errors are 40 to 45 dB down with respect to the output spectrum. The difference between the total distortion (which is the sum of the nonlinear and the noise distortion present in the output) and the model error varies between 10 and 20 dB. This shows that the model explains a large part of the nonlinear behaviour of the device. Other models

Reference:

(such as a generalized memory polynomial [2]) can obtain similar results, but they impose less structure, and tend to require more model parameters.

**Conclusion**

A parallel Wiener-Hammerstein model is proposed to explain the nonlinear behaviour of a broadband RF Doherty power amplifier. The proposed model obtains promising results, comparable to other modeling approaches that impose less structure, and that use more parameters in the model.

**References**


**2.7.2 Nonlinear RF Measurement and modeling: going beyond the NVNA**

*Maral Zyari, Yves Rolain*

**Funding: The science foundation Flanders (FWO)**

Characterizing the nonlinear behavior of systems operating at RF frequencies became popular during the last years. Mainstream measurement setups use CW or two-tone excitations under variable impedance loading. They mainly provide power sweep capability at a fixed frequency. Extracted Figures Of Merit (FOM) allow a comparison of systems under standard operation but lack the expected modeling capability.

![Figure 34: Schematic of the proposed setup](image)

Combining the intuitive S-parameters measurements and local description of the nonlinearity allow one to go beyond the quasi-static characterization. In the current state of the art, the nonlinearity is characterized first. Next, the frequency dynamics are ‘glued’ to the process. What we propose here is the opposite approach, as we consider the dynamics of the systems first, and model the nonlinearities in the next step. This approach requires a new measurement instrument specifically designed to handle modulated measurements. The extraction of the Best Linear Approximation (BLA) enables to measure a local linear dynamic model for the system that is appropriate specifically for the applied signal type.

In order to be able to characterize the dynamic nonlinear behavior of a system we need new instrumentation to start with that has all the capabilities of the first generation devices and extends
them for modulated signal handling. Our solution is to extend the Nonlinear Vector Network Analyzer (NVNA) with two phase coherent multi-tone modulated source for two-port operation and a controllable impedance tuner to present a known impedance over the modulation bandwidth. The suggested setup includes the instrumentation below:

- An NVNA with the addition of a number of amplifiers and attenuators at its ports to make sure that it is capable of handling sufficient power.
- An Arbitrary Waveform Generator (AWG) is used in the setup with a modulation bandwidth in excess of 100MHz.
- A four chariot mechanical tuner to control the output loading impedance.
- The measurement software needs to be flexible enough to allow various sweeps for different operating points, as the final goal is to have a setup which allows the user to bring the actual operating point of the measurement as close as possible to the desired one.

To speed up the measurement procedure, modelling of the frequency response function of the tuner is considered, which is not as easy as it may look, as the model has 9 parameters and the system is a MiMo system. So we have tried to reduce the number of parameters to be estimated from 9 to 2 by taking into account that the tuner has a symmetric physical structure. By looking into the time domain response of the system, we observe a multi-echo behavior, which is to be estimated.

2.8 HIGH FREQUENCY DESIGN AND CHARACTERIZATION

2.8.1 Integration of state-of-the-art analysis and modeling techniques in the early design states of high frequent power amplifier design

Piet Bronders and Gerd Vandersteen

Funded by Center for model-based system improvement - From Computer-Aided Engineering to Model-Aided Engineering (SRP19)

Efficient power amplifier designs trade off the power efficiency and the nonlinear distortion of the amplifier. This leads to complex amplifier structures, such as Doherty amplifiers, where the nonlinear interaction of two or more amplifiers is combined to improve the performance.

Current design strategies of complex amplifier structures use relatively simple design strategies, usually based on one or two-tone tests. State-of-the-art analysis techniques, such as the use of multisines and the Best Linear Approximation (BLA), are only used in the final stage of the design to verify the nonlinear performance of the complete system.

The targeted application of the power amplifier under design most likely introduces a modulated signal at the input port of the device. It goes without saying that the simple one or two-tone design techniques, which were chosen for their ease of use, can only result in rough estimates of the correct device behavior under the modulated conditions. Thus the design would have to be properly refined by optimization in further design stages where actual modulated signals are applied to the input ports of the device. The initial design step thus only serves to produce adequate starting values for the optimizer used in subsequent stages. Accuracy of the design parameters is thus relinquished in favor
of simplicity. Usage of a multisine as modulated signal, and as a result the entire theoretical framework that has been constructed to support this signal, is a possible way to immediately take into account the correct nonlinear and dynamic behavior at the initial design stage of the power amplifier.

The aim of this PhD research is to integrate the recently developed BLA modeling techniques (developed for both time-invariant and time-varying systems) in these early design stages of the power amplifier. The nonlinear interaction between two amplifier modules can either be seen as a nonlinear or as a time-varying effect given the time-varying modulation and the carrier. Hence, the general BLA theory for time-varying systems is an ideal candidate to setup a theoretical framework that enables the systematic design of complex amplifiers in a more efficient way. This will require the extension of the BLA theory for time-varying systems, as well practical realization of the proposed design strategy.

The current main research goals for this project are the following:

- Getting familiar with the current design techniques using one or two tones and the design of efficiency enhanced power amplifiers which will include Doherty amplifiers, Envelope Tracking amplifiers and the Chireix outphasing technique.
- Introduction of the BLA modeling techniques by creating a theoretical framework usable for power amplifier design. The resulting design technique should thus not only be simple to implement, but should also remove the blind optimization that is inherent to most of the advanced RF power circuitry by giving the designer better insights and concrete directions on how to improve the design.

2.8.2 Model driven design of high performance microwave filters

Evi Van Nechel, Yves Rolain

Funding: Funding by the Flemish Government (Methusalem)

Microwave filters are steadily evolving towards the use of more complex transmission line structures as building blocks. This is needed to cope with the highly demanding specifications of modern telecommunication equipment.

The design procedures that are used to realize these filters however have not evolved at the same pace. They still rely on the use of empirical design equations that are borrowed from standard line structures. The lack of accuracy that results from this crude approximation is then filled using massive numerical optimization based on EM simulations. This process is both time-consuming and blocks the intuitive insight in the operation of the device that is so useful to any designer.

To circumvent these disadvantages, we propose to introduce models in the design process. As the “one model does it all” was already proven to be unsuccessful in previous attempts, we propose to use a different paradigm, where a specifically tailored model is used for specific design tasks.

More specifically, we intend to use a circuit based model to adequately and accurately describe the elementary building blocks of the filter structure. This scalable model will be used to introduce the
boundary conditions and the process limitations of the technology in a very early stage of the design. Initially, this allows to close the design cycle early and adapt the prototype. In a second stage, we hope to introduce this additional knowledge in the approximation and the design of the initial prototype. If successful, this will fundamentally modify the way filters are designed.

Despite the higher quality that is aimed at for the models of the elementary sections, there will still be a need for a final fine-tuning of the realization obtained earlier. To this end, we plan to use a high fidelity scalable model for the complete structure over a limited span of the design variables. This can then be used to fine-tune the design and to determine the sensitivity and the associated yield to be expected for the circuit.

2.8.3 Using the Best Linear Approximation in circuit design

Adam Cooman and Gerd Vandersteen

This research is sponsored by the Strategic Research Program of the VUB (SRP-19), Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen)

The need for faster and more efficient electronic circuits pushes the devices more and more into their non-linear operating regions. The amount of non-linear distortion generated by a circuit becomes an increasingly important part of the circuit’s specifications. Most of the designers of analog electronic circuits use a linear framework to build their circuits. When the design is finished, the distortion levels are determined by simulations on the global circuit. If distortion specifications are not met, the origin of the distortion is not easily identified.

Current solutions to finding the dominant source of distortion rely on Volterra theory. These techniques are complex and lie far from the classical linear framework. Hence, they are not widely used during the design of electronic circuits.

Our goal is to introduce the Best Linear Approximation (BLA) into the design of analog circuits. The BLA allows the approximation of a non-linear block by a linear block where the distortion introduced by the system is modelled as noise. Linear systems and noise are concepts designers are very familiar with, so they would be able to adapt quickly to BLA-based methods. Using the BLA, information about the non-linear behaviour of the circuit can be introduced early into the design flow, preventing problems at the end.

There are two main research goals:

1. Develop a simulation-based Distortion Contribution Analysis (DCA) that determines the dominant source of non-linear distortion in a complex circuit.

2. Build a set of design rules to give a designer hints on how to decrease the amount of non-linear distortion generated by a circuit.

We started by looking into the DCA for operational amplifiers and continuous-time filters [1]. The method works fine at low frequencies but, at higher frequencies, the terminal impedances of the stages come into play and limit the use of the method developed in [1]. An extension of the method to include the full port representation of the stages already shows nice results [2], but the technique
is currently still limited to dominantly linear circuits. We are working towards the fast extraction of the MIMO BLA to overcome this limitation.

In a next stage, we will study how the methods can be used for the design of mixers, power amplifiers, Phase Locked Loops and finally: a full transceiver.

**References**


### 2.8.4 Macro-models for the Design of Microwave Filters

*Matthias Caenepeel, Yves Rolain, Fabien Seyfert (Sophia-Antipolis), Martine Olivi (Sophia-Antipolis)*

*Funded by the Research Council of the Vrije Universiteit Brussel, The Research Foundation Flanders (FWO-Vlaanderen), the Flemish Government (Methusalem Fund METH1), and the Belgian Federal Government (Interuniversity Attraction Poles programme IAPVII, DYSCO)*

The design of microwave narrow-band bandpass filters often depends on brute-force electromagnetic (EM) optimization. These optimization procedures are numerically expensive, which makes the design process very time-consuming. Moreover the EM optimizer does not provide any physical insight in the filters behavior as a function of its design parameters. The aim of this research is to generate models that are numerically cheap and provide insight in the filters behavior.

An example of a microwave filter realized in a microstrip technology can be seen in Figure 35. The final design step consists in correctly dimensioning the geometrical values $t_{in}$, $t_{out}$, $g_{in}$, $g_{out}$ such that the filters response (S-parameters) meets the specifications. A model that links these geometrical parameters to the response is often called a macro-model. State-of-the-art macro-models interpolate of a set of well-chosen known "root" frequency response functions (root FRFs) that depend on the values of the design parameters (in this case the geometrical parameters) [1]. These "root" models are FRF models that are obtained by a computational expensive EM solver. The selection of these root models is a key issue as it determines both the effort needed to extract this model and the final accuracy of the macro model. These models are black-box models since they do not incorporate any prior knowledge about the system. Since we are dealing with filters, we propose to develop a modeling procedure that takes into account some knowledge about the filter. Rather than using the FRF of the filter, we use its electrical or coupling parameters to model it.

The design of narrow-band bandpass microwave filters is widely based on coupling matrix theory [2] in which the filter is modeled at hand of a low-pass coupled resonator circuit (Figure 36). In the same way as classical lumped element synthesis, the design process begins therefore by the derivation of a characteristic function, meeting the filtering specifications, which needs, in a second step, to be realized by a circuit. Next these circuital parameters (the coupling parameters $M_{ij}$, $R_{ij}$) must be implemented physically in a certain technology (e.g. microstrip technology shown in Fig. 1) by
correctly dimensioning the filter. It is during this step that the heavy optimization processes typically pop up. An initial dimensioning of the filter is carried out by means of simplified empirical design curves relating the coupling values and the geometrical characteristics of the filter. These curves however typically ignore more complex interactions, such as loading effects of the resonators by the couplings, and must therefore be followed by a mandatory tuning step. Rather than performing this tuning step using an EM optimizer, we propose to model the coupling parameters as a function of the geometrical (design) parameters of the filter. Such models allow finding the physical dimensions of the filter for which the corresponding coupling parameters are as close as possible to the ideal ones found during the synthesis step.

The first step in the modeling process thus consists in extracting the coupling parameters from simulated or measured S-parameters. The challenge is that for various filters, several coupling matrices realize the same filter response (S-parameters). Current extraction procedures rely heavily on optimization techniques that adjust the electrical parameters of the low-pass equivalent circuit in order to fit the measured response. These methods, by construction, yield a single coupling matrix, that strongly depends on the initial starting point and that, in case of multiple solution topologies, does not necessarily correspond to the implemented circuit. To overcome this shortcoming, we developed a three stages extraction process. The first step derives a rational approximation of the measurements. The second step, finds all possible circuital realizations of the previously computed rational approximant, with a specified coupling topology. Eventually a third step, based on the analysis of several extractions results, allows to decipher the physically implemented matrix. More information about the parameter extraction procedure can be found in [3].

The next step is to use this information to model the filters behavior as a function of its geometrical design parameters. So far multivariate quadratic polynomials have been proposed to model the coupling parameters as a function of the geometrical parameters. Future challenges will lie in the choice of the values of the geometrical for which the filter must be simulated and finding the most suitable model structure for the coupling parameters.
2.9 MEDICAL MEASUREMENTS AND SIGNAL ANALYSIS

2.9.1 Estimation of respiratory impedance at low frequencies during spontaneous breathing using the forced oscillation technique

Hannes Maes, Gerd Vandersteen, Clara Ionescu (UGent) and Johan Schoukens

Funding: the Science Foundation Flanders (FWOAL662) and Center for model-based system improvement - From Computer-Aided Engineering to Model-Aided Engineering (SRP19)

The forced oscillation technique (FOT) is a non-invasive method to measure the respiratory impedance $Z_L$. FOT determines $Z_L$ by superimposing small amplitude pressure oscillations on the normal breathing and measuring the resulting air flow. Our research focuses on obtaining $Z_L$ at low frequencies (0.1-5 Hz) in a clinically practical way. The patient can continue tidal breathing during the measurement and is not to be impeded by the imposed pressure oscillations.

A fan-based FOT device has been developed and optimized in order to impose pressure oscillations with a high signal-to-noise ratio during spontaneous breathing. By use of a combination of feed forward compensation and a linear controller, a high quality pressure excitation signal can be generated [1].

Two main difficulties arise when estimating $Z_L$ using measurements at low frequencies obtained during spontaneous breathing.
1. Due to the change of lung volume during spontaneous breathing, the respiratory impedance will change over time. The response of the respiratory impedance to the pressure excitation will thus depend on the breathing pattern. In the ongoing work, the best linear time invariant approximation (BLTIA) defined in [2] is used. This leads to the approximation shown in Figure 37. The response of the respiratory impedance is considered independent from the breathing pattern.

2. The measured air flow contains both the breathing signal and the response of the respiratory impedance. Both generate energy in the same frequency range. Therefore, estimation techniques to separate both signals are tested in order to get an accurate estimate of the response to the pressure excitation and with that the respiratory impedance.

The aim is to first optimize the estimation results using the BLTIA. Simulations incorporating measured breathing patterns and viscoelastic models are developed to mimic real measurements. The developed estimation techniques are applied on real measurements and, if necessary, the respiratory impedance can be approximated by a real time-varying system.

References


2.9.2 Brain Tissue Differentiation and Characterization using Piezoelectric Actuators driven by multisine excitation

David Oliva Uribe, Ralf Stroop, Johan Schoukens and Joerg Wallaschek (University of Hannover)

Funding Related: Flemish Government (Methusalem)

This project is related to the estimation of the mechanical parameters of biological tissues (in particular brain tissue) using a piezoelectric tactile sensor (shown in Figure 38). The main purpose is to provide the tactile sensor a reliable measurement procedure for the differentiation of two biological materials with slightly differences (e.g. tumour and healthy tissue in brain). Potential applications of this research can be addressed in the development of assisting tools for intra-operative tumour delineation and tumour resection in neurosurgery, where is intended to help neurosurgeons with the difficult task of determining tumour boundaries during resection of brain tumours.

In order to have a reliable instrument that can be used in surgical procedures, it is necessary to enhance the capabilities of the tactile sensor system. This project involves the improvement in measurement time and accuracy of the sensor system using multisine excitation. In addition, we aim
to provide the sensor system with the function to characterize the mechanical properties by the estimation of viscoelastic parameters using system identification techniques.

At current, the tactile sensor has been successfully tested with tissue phantoms and ex vivo animal samples where it has been shown the capability of the sensor to differentiate minimal differences in tissue consistency. It is expected to perform in the short term, measurements on human pathological samples and the implementation of the measurement setup directly in the operation theatre.

Figure 38: Left: Piezoelectric tactile sensor. Right: Comparison of two frequency response functions to show the effect of the load in the sensor system. Contact with soft material will lead to changes in the maximum amplitude and the resonance frequency.

This project is done in cooperation between the VUB dept. ELEC, the Institute of Dynamics and Vibration Research of the Leibniz University of Hannover and the Neurosurgery Clinic of the University Hospital of Bochum.

Figure 39: Left: Electromechanical model of the piezoelectric tactile sensor. Right: Tactile sensor in contact with animal brain tissue.
3. Development cooperation

3.1 DEVELOPMENT COOPERATION IN CURRICULA BUILDING AND ACADEMIC RESEARCH

The department ELEC has a long tradition in development cooperation with universities and institutes in the South. Projects with funding from the Belgian government for Development Cooperation already were undertaken from the eighties of last century with the Moi University in Eldoret Kenya, Anton de Kom University in Paramaribo, Surinam and ESPOL in Guayaquil, Ecuador.

With the support of the VLIR (Flemish Interuniversity Council) Prof. Leo Van Biesen from ELEC became leader (promoter) in two development cooperation projects in central Africa. Both projects, described in more detail in the next sections, aim to contribute in the rebuilding of the academic and/or professional education programmes, in improving the research facilities and in the formation by Master degrees and/or PhD of future academic staff personnel. Such projects belong either to the funding group of the VLIR Own Initiative group with partners in the countries of the development cooperation priorities of the Belgian Federal and Community governments with a medium term duration between 3 to 5 years, either to the VLIR Institutional University Cooperation programme (IUC) that facilitates a 12-year partnership between a university in the South and Flemish universities and university colleges. These programmes support the partner university in its triple function as provider of educational, research-related and societal services. It aims, as such, at empowering the local university as to better fulfil its role as development actor in society.

3.2 PROJECT WITH ISTA, KINSHASA, CONGO

The VLIR Own Initiative project with ISTA (l'Institut Supérieur de Techniques Appliquées), the largest engineering education institution in Kinshasa, the capital of the democratic republic of Congo (DRC), aims in upgrading the polytechnic institute towards a technological university. The original project title, as well as the description and reports are written in French only (Projet d'aide à la transformation de l’Institut Supérieur de Techniques Appliquées de Kinshasa en université technologique).

The Flemish promoter is Leo Van Biesen (Vrije Universiteit Brussel department ELEC). The local promoter is Prof. André Ahuka Shamba (ISTA).

The project started on December 31st of 2009 and will end on December 31st of 2014. The financial support of the project accounts 309 k€.

The project succeeded a short term mini project funded in 2008 also by the VLIR that allowed identifying the most relevant areas in which institutional cooperation with ISTA could be set-up. To overcome the shortage of skilled engineers in the DRC, the highest political authorities of the DRC agreed - within the PADEM framework - to transform ISTA into Université Technologique de Kinshasa (UNITEK), which will be responsible for the training of both civil engineers and industrial engineers. The project’s goal is to contribute to this transformation. To optimize the use of available resources
and skills, the focus is put on the information and communication technology "ICT" and especially to electronics, computer science and telecommunication. The project focuses on three main categories: (1) Revision and development programs in ICT (in collaboration with VUB, KUL, Erasmushogeschool) (2) Training of Trainers (scholarships and internships at the VUB), (3) The equipment of laboratories in ISTA, in particular the development of WiMAX and WiFi networks.

In 2013 two senior assistants of ISTA, Joséphine Mpole and Jean Lukwesa, visited the ELEC department for 3 months training. Next to following lectures and courses on the master level of engineering education programmes, large attention was attributed to the development and the setting up of new laboratory experiments for engineering students in telecommunication. The set-ups were developed at ELEC and the material for future duplication was shipped to ISTA en Kinshasa.

Patrick Kapita from ISTA is following the Master in Applied Computer Science at the engineering faculty of the VUB.

The local promoter, Prof. André Ahuka, and the head of ISTA (director general) Prof. Pierre Kasengedia, also visited ELEC in 2013 for 2 weeks.

3.3 UIC PROJECT WITH THE UNIVERSITY OF BURUNDI, BUJUMBURA, BURUNDI

The VLIR Institutional cooperation with Université du Burundi, Burundi, is a project with a duration and 12 years that started in 2011. The Flemish programme coordinator is Prof. Filip Reyntjens (University of Antwerp) and the local programme coordinator is Prof. Samuel Bigawa. The project consists of 5 major subprojects and 1 subproject responsible for the management and reporting. Prof. Leo Van Biesen (ELEC) is promoter of subproject 5 that deals with new communication and information technologies and support to the library. The local project leader is Prof. Léonard Batururimi.

The 5 subprojects are listed below:
1. Strengthening teaching and research capacity in basic sciences and pharmacy.
2. Contribution to the improvement of medical education, research and to the quality of health care in the community
3. Rural development and food security in the provinces of Ngozi and Kayanza
4. Capacity building for teaching and research in the Faculty of Law
5. New communication and information technologies and support to the library

The Université du Burundi (UB) is the only public university of the country and is located in the capital Bujumbura. It started an IUC programme in 2010 that fully subscribed to the PRSP (Poverty Reduction Strategy Papers) development priorities of a post-conflict area. In this context the University of Burundi is to be reinforced in its role of development actor towards society through interventions of higher education and research. As such, a partnership with the Flemish universities and university colleges is established and sustainable scientific cooperation implemented.

The IUC programme encompasses 5 thematic projects, basic sciences, rural health, food security, development of the Rule of Law and ICT and library development. Most of the projects are campus-
based but projects 2 and 3 operate in the North of the country in the provinces of Ngozi, Kirundo and Muyinga. The partnership proudly carries the label 'Kubadilishana Mawazo, Kugeuza Maisha' or 'Sharing minds, Changing lives' in Kiswahili.

For more information on the programme, you can also visit the UB - VLIR-UOS website (http://www.vliruos.be/en/ongoing-projects/overview-of-ongoing-projects/iuc/institutional-cooperation-with-ub,-burundi/).

The local promoter of subproject 5, Prof. Léonard Batururimi, and the Dean of the faculty of engineering at the University of Burundi, Prof. William Sahinguvu, visited the department ELEC in 2013 for 2 weeks. Eloge Bapfunya received a 3 months training in ICT and telecom at the departments ELEC and ETRO of the VUB and Egide Nshimirimana is following the Master in Applied Computer Science at the engineering faculty of the VUB.

The yearly envelope of subproject 5 is about 75 k€.
4. Education

4.1 THE INTRODUCTION OF THE BACHELOR-MASTER STRUCTURE

Since the academic year 2004-2005 the "bachelor - master" structure (replacing the candidate - licentiate structure) has been introduced. The initiative for this thorough interference in the programmes of higher education was the Bologna Declaration. The Ministers of Education of 31 European Countries gave in 1999 the start to uniform the higher education in Europe. Although the Bologna process creates convergence, the fundamental principles of autonomy and diversity are still respected. The aim of the Bologna Declaration is to improve in Europe the exchangeability of degrees, the free mobility of students, quality assurance and a flexible study package by introducing credit systems.

4.2 BRUFACE (WWW.BRUFACE.EU/EN/)

Brussels Faculty of Engineering (in short "Bruface") is an initiative of the two universities in the centre of Brussels. The Université Libre de Bruxelles (ULB) and the Vrije Universiteit Brussel (VUB) jointly offer a broad spectrum of fully English taught master programmes in engineering.

Starting from the academic year 2011-2012 Université Libre de Bruxelles and Vrije Universiteit Brussel jointly organise the following English taught Master of Science (MSc) programmes

- MSc in Architectural Engineering
- MSc in Chemical and Materials Engineering
- Options Materials, Process Technology
- MSc in Civil Engineering
- MSc in Electromechanical Engineering
- Options Aeronautics, Energy, Mechatronics-Construction, Vehicle Technology and Transport
- MSc in Electronics and Information Technology Engineering

The Université Libre de Bruxelles (ULB) and the Vrije Universiteit Brussel (VUB) are both active in several international higher education networks including T.I.M.E.\(^1\) and UNICA\(^2\).

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\(^1\) Top Industrial Managers Europe: is a network of 51 leading Engineering Schools and Faculties and Technical Universities which offers, through a system of voluntary bilateral agreements between its members, promotion and recognition of academic excellence and relevance to the international labour market in the form of Double Degrees in engineering and in related fields.

\(^2\) Is a network of 42 Universities from the Capital cities of Europe, with a combined strength of over 120,000 staff and 1,500,000 students. Its role is to promote academic excellence, integration and co-operation between member universities throughout Europe.
4.3 COURSES LECTURED IN THE FACULTY OF ENGINEERING

4.3.1 Regular Courses, Bachelor Degree

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<th>Lectures and practical courses</th>
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<td><strong>Electromagnetism - Prof. Y. Rolain</strong>&lt;br&gt;Starting from the very general Maxwell equations, we end up with the differential equations that govern the behaviour of the electrical field in free space. This simple differential equation is subsequently solved using simple mathematical functions in different geometries and field configurations. These use-cases contain both real engineering problems and fair approximations of more complex situations. This includes but is not limited to the propagation of electromagnetic waves in free space, or in a guiding structure. Examples used in the course are the coaxial cable, the rectangular metal waveguide and the flat dielectric waveguides. The dissipative behaviour of the electrical field results in an in-depth analysis of the Skin-effect in plane and cylindrical conductors. A lot of time and effort is spent to cover the theory and the practical applications of the transmission lines. A whole collection of techniques are explained theoretically and are next illustrated in the tutorials, the exercises, and the laboratory work. Some examples are: the S-parameters, the reflection coefficient, the VSWR, the reflectometric setup, and the single- and double-stub matching techniques. Finally some energetic concepts of the propagation of the electromagnetic fields in the free space are touched. The vector of Poynting is used to introduce the basics of the theory of the antennas and to calculate the power balance of a radio propagation. The course is split in the Lectures and practical work.</td>
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<td><strong>Network Analysis and Synthesis - Prof. R. Pintelon</strong>&lt;br&gt;Part 1: Linear networks and Nonlinear networks&lt;br&gt;Part 2: Synthesis of filters</td>
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</tr>
<tr>
<td><strong>Basic Electricity - Prof. L. Van Biesen</strong>&lt;br&gt;2 major goals are to be attained:&lt;br&gt;1) Getting insight in the use of mathematical tools to describe the most important experimental classical laws. One starts from the 4 equations of Maxwell. It is demonstrated that when including the law of Lorentz, which expresses the interaction between electrical sources and mechanical forces, any electrical problem can be solved. To achieve this task an introduction on Newtonian potentials is given. Using the theory of Helmholtz, it is shown that the approach of potentials yields an adequate and concise method to tackle electrical problems. This potential theory is also of use in other physical domains then electricity, such as mechanics and hydraulics, and, therefore, this theory is kept as fundamental as possible. The mechanism of conduction in conductors is studied using Ohm’s law in local and global form. The resistance is studied as well as the current and voltage distributions in a conductor (calculus methods of Hopkinson). Attention is always drawn on the methods to predict the responses and influences when an electrical source (in scalar or vector form) is applied to a physical system. A mathematical model describing a battery is studied. The same approach to model the sources is also treated for magnetic and dielectric media, whereby an energetic balance is deducted.&lt;br&gt;2) Introduction to network analysis and theory.</td>
<td>7</td>
</tr>
</tbody>
</table>

4.3.2 Regular Courses, Master Degree

<table>
<thead>
<tr>
<th>Lectures and practical courses</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capita selecta Telecom - Prof. L. Van Biesen</strong>&lt;br&gt;The content changes year by year since the selected subjects in telecommunication are chosen in function of the industrial expectations and realisations. Subjects treated in the recent years are e.g.: xDSL and ADSL and VDSL2 in particular, GSM (GPRS) networks, Wi-Fi and meshed networks, RFID, UMTS, WiMAX, SACD coding versus Dolby or DTS, GNSS, Tetra, IP-TV, UWB...</td>
<td>3</td>
</tr>
</tbody>
</table>

3 The language of tuition of the bachelor courses is Dutch
4 The language of tuition of the Master courses is English and/or Dutch
### Voice Image Coding Media and Systems - Prof. L. Van Biesen and Prof. G. Vandersteen

<table>
<thead>
<tr>
<th>Part 1:</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1: Introduction to telephony. The telephone set, general description, the transmission of the signals. The side-tone circuitry, the complete telephone set, making a connection, the bell circuitry, and the switchboard.</td>
<td>6</td>
</tr>
<tr>
<td>Chapter 2: Characteristic parameters of transmission lines. The line types and their parameters. Aerial lines, cable lines and coaxial cables. The influence of the frequency on the characteristic impedance and the propagation factor (attenuation and phase). Improvement of the quality of cables. Practical telephony cables are treated (Belgacom, BT, France Telecom, KPN, ETSL-models).</td>
<td></td>
</tr>
<tr>
<td>Chapter 4: Telephony using carriers.</td>
<td></td>
</tr>
<tr>
<td>Chapter 5: Pulse code multiplexing. The general principles. The non-linear quantisation. The A and μ-law. The signal-to-quantisation noise diagram. Multiplexing. The composition of a raster and multiraster. PCM. The line transmission in PCM. Line coding. The PSD of NRZ-coding, RZ and bipolar RZ-coding, HDB-3 coding. Regeneration. The correction preamplifier and the eye-diagram and errors caused by the regenerator. 'Digital Subscriber Line' technologies are studied. HDSL, ADSL and SDSD modems are treated. Cross-talk problems are examined (NEXT, FEXT). De theoretical channel capacity for ADSL, SDSD and VDSL are derived and compared to practical measurements.</td>
<td></td>
</tr>
<tr>
<td>Chapter 6: Markovian processes. The infinite switching board, the switching board with losses. The finite switching board with a queuing line.</td>
<td></td>
</tr>
</tbody>
</table>

### Physical Communication - Prof. L. Van Biesen and Prof. G. Vandersteen

<table>
<thead>
<tr>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problems with radio communications: used frequencies, propagation paths, and modulation methods. Advanced study of AM modulations (conventional AM, DSB, SSB, VSB, QAM), angle modulations (WBFM, NBFW, FM), digital modulations (FSK, PSK, DMT). Study of the properties of transmission channels and SNR studies of demodulators. Many practical circuits and schemes are treated. Study of the atmosphere as channel for radio and satellite communications. Bundle profiles of antennas and (linear) antenna-arrays. Study of reflection, transmission, diffraction, refraction and scattering...</td>
</tr>
</tbody>
</table>

### Measuring and Characterizing Non-Linear RF Systems – Prof. W. Van Moer and Prof. N. Bjorsell (University of Gävle, Sweden)

Understanding the working principles of RF components. Gaining insight in the nonlinear behavior of RF components and systems. Knowing how to measure the nonlinear behavior of RF systems. Acquiring knowledge of linearization techniques. Gaining insight in the working principle and special requirements of RF measurement equipment able to measure the nonlinear behavior. Selecting the correct model for the measured system. Getting in contact with state-of-the-art measurement and modeling techniques as well as recent research topics. | 4 |

### Bioinformatics and Datamining – Prof. J. Schoukens

The course describes data-mining methods in bioinformatics. The biological content is kept to a bare minimum. The focus is on probabilistic modeling (sequence alignment as dynamic programming, Expectation-Maximization, Markov Chain Monte Carlo methods). The content is very relevant to data-mining applications outside bioinformatics. The emphasis lies on the basic concepts underlying probabilistic methods and how they are transformed into practical applications. | 4 |

### Industrial Measurement Environments - Prof. L. Van Biesen and Prof. Y. Rolain

This course is dedicated to industrial metrology. The learning objective consists in the study of the building blocks of instrumentation in metrology (measurements) and to adapt those to industrial requirements and environments. Since the content of this course is highly based on technology, it evolves strongly. Therefore, the students will receive updated information on standards and specific realizations, which are demonstrated by on site industrial plant visits. After completion of the course, the students should be able to analyse industrial measurement problems, to conceive and to plan metrological installations, to integrate and to network them. | 4 |

### RF/Microwave Design Techniques: from Datasheet to Product - Prof. Y. Rolain and Prof. G. Vandersteen

The step from a prototype to a commercial product is larger than seen at first sight. To cut the price of the final product, it is important:
- to reduce the amount of tuning and testing;
- to increase the yield of the product taking into account the processing variations (design for manufacturability); and
- to protect the circuit against Electro-Static Discharge (ESD) by manipulation / handling the circuit.

The aim of this course is to close in the gap between the theoretical knowledge on RF/microwave design, and the design of a commercial product. Starting from the knowledge on electromagnetics and RF/microwave amplifier design, all design aspects of complete RF/microwave systems are covered in the course. This includes the system-level design, the design of different RF/microwave sub-systems (such as mixers, amplifiers, hybrids, filters, antennas ...), their design for manufacturability (production tolerances, Design Rule Checking (DRC) ) and their protection to the manipulation by the user (e.g. ESD-protection). | 4 |
Aims and Objectives
The objective is to make the future engineers aware of the problems and solutions that need to be considered when turning a prototype RF/microwave system into a product. He/she will therefore combine past experiences/courses on telecom and RF/microwave design, and extend/apply this knowledge to turn prototypes into real products. The objectives are therefore to
- perform a system-level study of a complete transceiver system and make the trade-offs between the different RF/microwave sub-systems;
- design the different RF/microwave sub-systems;
- use of field solvers and measurements of prototypes to predict the response of critical passive structures (filters/hybrids/antennas);
- consider the ESD protection, when assuming that the user might physically touch the LNA input or the antenna;
- consider the manufacturability by taking into account the DRCs of the technology and the yield coming from uncertainties on the components, models and technology.
The main focus of this course is to apply the information given in the lectures (on ESD-protection, yield computation/optimization), onto a practical RF/microwave design. Starting from specifications, an ESD-protected, yield optimized RF/microwave receiver/transmitter needs to be designed, realized and measured.

CAE-tools for the Design of Analog Electronic Circuits – Prof. G. Vandersteen
Analysis and design of analog electronic circuits is done using computer aided engineering (CAE) tools. The methods used comprise dc analysis, ac analysis, transient analysis, harmonic balance analysis, shooting method, large-signal / small signal analysis,... It is evident that every tool is optimized to analyze a specific type of circuit or analysis. Take for example the transient simulation which is available in SPICE. This transient simulator is not suited for analyzing nonlinear microwave circuits or for the noise analysis in mixers. To solve this problem, simulation techniques such as harmonic balance were developed. Harmonic balance assumes that all signal are either periodic of quasi-periodic. This makes harmonic balance unsuited for non-quasi-periodic signals, but makes the technique superior for the analysis of nonlinear microwave circuit and the noise analysis of mixer.
The aim of the course is to teach the future engineer the different available simulation tools. This way, he/she should be able to judge which CAE-tool is the most appropriate for solving his/her design or analysis problem. Besides the choice of the analysis tool, there is also the problem of setting the simulation parameters correctly. This requires some background in the actual implementation of the simulations techniques. Hence, a theoretical background of the different simulation techniques must be given in the course. In addition to the theoretical aspect, it is important to have practical experience with the simulation tools. This will lead to a future engineer which does not lose time by simulating with a sub-optimal simulation tool.

Measuring and Modelling of Nonlinear Systems – Prof. J. Schoukens
Linear system theory is a simple but very successful description of nature although most systems are nonlinear. For that reason it is important for an engineer to know how the presence of nonlinear distortions can be detected. On the basis of this information, she/he should decide if linear system theory is still applicable to solve his problem.
On the other hand, some systems are intrinsic nonlinear. Till recent, it was very hard to measure these characteristics. New measurement equipment allows nowadays to characterize also these nonlinear systems. For that reason it is necessary that our engineers have a sufficient background to access this new possibilities.
Applications exist in the mechanical, electrical, electronic and microwave fields. This course offers a good basis to recognize, understand and deal with such nonlinear problems.

Identification of Dynamical Systems - Prof. R. Pintelon
This course describes the various steps one has to go through for obtaining a linear dynamic model of a process. It starts with the choice (design) of the measurement setup, the choice (design) of the excitation signal, the choice of the parametric model (discrete time, continuous time, parametric versus non-parametric noise model...), the estimation of the parametric model (identification toolboxes in Matlab), till finally the model selection and the model validation. Hereby the influence of each error source (stochastic measurement errors, systematic measurement errors, non-linear distortions, time-variant effects, model errors...) on the final result is studied in detail.
Each step is illustrated thoroughly by means of real life examples.

Signal Theory - Prof. L. Van Biesen and Prof. I. Markovsky
Signals and information and signal classification, the terminology, the elements in a communication system, the kind of signals: the deterministic ones, stochastic signals, periodic signals. Use of basic functions and integral transformations:

Advanced Control Theory - Prof. R. Pintelon and Prof J. Swevers (KUL)
4.4 DESIGNING SYSTEMS FROM CONCEPTS: THE PING-PONG TOWER PROJECT

The design of complex systems demands that engineers possess significant set of abstract system-level thinking skills. Engineering students therefore need to be exposed to the art of solving problems systematically and have to learn the limitations and the backsides of ad-hoc methods, to ensure that they should only turn to these methods as last resort alternatives.

To start the process of system-based thinking early, we use an experience based learning project during the students’ fourth semester to awaken them to a systematic engineering approach. This project is taken by all engineering students at our university. As a consequence, all the students are taught the crucial concepts that can lead to the inclusion of sustainable development in engineering practice irrespective of their final specialization in electronics, mechanics, chemistry....

A feasible toy engineering problem is proposed that includes a lot of practical engineering problems:

The process to be controlled is the stabilization of the height of a Ping-Pong ball floating in a user-controlled airflow inside a transparent Plexiglas tube. Although students get a strong guidance towards good engineering practice, they have to choose the method and decide on the practical implementation themselves.

Pedagogically speaking, the major advantage of this project is that the students gain a lot of engineering attitudes. Firstly, they gain hands-on experience in a wide range of engineering applications: digital electronics, analog electronics, power electronics, control engineering, signal processing, optical system design, and computer engineering all have their role to play in the project. Secondly, they gain the insight that system-level thinking leads to complexity reduction and problem partitioning, and therefore allows to solve large-scale problems that would remain untracktable otherwise. They learn that walking the lines of a systematic design framework leads to well-understood, high-quality, reproducible and reusable results.

In the next section, we situate the project in the engineering study. Afterwards, we explain the different steps the student should take. Then we describe which engineering attitudes the students gain throughout this project.
4.4.1 Situating the project

At the Vrije Universiteit Brussel, all engineering students follow the same courses during their first four semesters of their bachelor education. In order to help the engineering students to choose between different specializations, they are confronted with four different engineering problems in their fourth semester, one in civil engineering, one in chemical engineering, one in mechanical engineering and one in electronic engineering.

The ping pong tower project has a number of inherent advantages due to its broad range of possible solutions. The solutions that can be built

- are a combination of analog and digital electronics;
- use both hardware and software solutions;
- have the dynamics of the system are in a practical range, making it possible to demonstrate instabilities;
- involve no safety risks due to the use of low voltages;
- make it possible to introduce the students to control theory.

4.4.2 The project

The students need to control the height of a Ping-Pong ball in a tube by means of a fan which blows air in the tube. They need to set and measure the height using a PC. Every group needs to present its work in a scientific way by the end of the project to train their scientific presentation skills.

The goal is that the teams build up a complete solution starting from available basic building blocks:

3. A variable speed fan blows air into a Plexiglas tube whose diameter is 4 mm larger than the Ping-Pong ball.
4. An example interface between the PC and a PIC-based microcontroller board which has a USB connection to the PC. The firmware of the microcontroller board contains the implementation of an analog-to-digital convertor and a PID controller with user adjustable gains besides the present USB interface to the PC. The simple PC program allows the user to set the wanted height and read the actual height of the Ping-Pong ball from the microcontroller board.
5. Various pre-existing modules are available since – due to the limited timeframe – it is impossible that the students build everything from scratch. The pre-existing modules are an ultrasonic position sensor module, a fan power steering module, a microcontroller board and a simple PC program.
4.4.3 From concept to working system

The key idea is to illustrate the usefulness of a top-down design for the control of complex systems. The students are thought to first reason at the system level using simple system models. Next, good engineering practice rules are to be used to specify the modules separately. Then, the selected modules are designed separately from a set of discrete components. The final challenge is to combine everything in a performing system.

During the first one and a half day, the students try to understand the problem by slicing it into smaller sub-problems. During the next day, they decide on their strategy and implementation. The next two days, they spend on implementing their different blocks. The final one and a half day before the presentation, they need to combine the different sub-blocks and tune their controller.

4.4.3.1 Step 1: Understanding the problem

What is a system? This question is the key problem tackled in this phase. Therefore, the students get a short introduction to the system-level concept.

They discover the usefulness of a block diagram of their complete system to support high-level reasoning. They partition the problem into different logical blocks with a smaller complexity. They also have to think about the analog and/or digital interfaces between the different blocks. This brings them to a block diagram like Figure 1 the figure below.

For the first time in their education, the students have to deal with

- the sensors and sensor data,
- the controller,
- the power steering stage for the fan,
- interfacing the digital data between a PC and a microcontroller, and
- the design of a user-friendly interface on the PC.

![Block Diagram](image)

Figure 1. A possible block diagram for the problem.

In order to be able to interconnect all the blocks, they need to decide on the interfaces between the different blocks. Therefore, they write down specifications for the different blocks. The interface specifications of the pre-existing modules are given in a datasheet format. These specifications let
the students reflect on the interconnection and make them acquainted with datasheets. The power steering module – for example – has two different inputs: an analog voltage and a digital PWM input that are both controlling the output voltage. They have to decide which type of signal they are going to use and consider the influence of their choice to the rest of the system.

The students experience that most design problems do not have a unique solution, unlike what they found from their courses in mathematics. Although the control loop will always look the same at system level, the block diagrams of the different groups can differ. Some groups implement for example the controller in the PC program, which moves the interface between the PC and the system directly to the controller input. Such choices have a large impact. The students learn to weight off the different advantages and disadvantages, and learn to slice a complex problem into tractable and independent, co-operating blocks.

4.4.3.2 Step 2: Strategic thinking
Due to the limited timeframe and their lack of practical experience, it is not possible for every group to build up a complete solution from scratch. Therefore, depending on the number of students in the group, two to three blocks are selected for a design from scratch, depending on the student’s own interest. This allows training their negotiation skills and expressing their leadership. They use the pre-existing modules for the other blocks.

The groups define work packages that fit the workload of two students for the next three days. Since they work in teams of two students, they all feel engaged in the project. They can make their own contribution to the project without being overshadowed by one brilliant student in the group who would otherwise be designing the complete project.

Every team then focuses on the design strategy of their specific block. They have the freedom to choose their approach freely. The sensor – for example – can be realized under different forms: an ultrasonic height sensor, an optical scan line, an image-based webcam sensor, ... They are also encouraged to propose their own solutions, although the feasibility needs to be checked beforehand.

4.4.3.3 Step 3: Creating the different blocks
When they develop a specific block, they learn that the system-based approach used before can be reused. The specific problem is further split into different sub-blocks until they reach the level where building and understanding each part becomes straightforward. Then, each element is realized and tested to meet the prescribed specifications. Afterwards, those elementary parts are combined into subsystems.

For the ultrasonic sensor, this system-based approach results in the design of a transmitter, a receiver and a signal processing unit. The transmitter generates a pulsed 40 kHz signal together with its envelope. The receiver cleans up the measured reflected burst and generates a discrete envelope of the received signal. The signal processing unit measures the time T between the transmitted and reflected burst, which is proportional to the distance L between the sensor and the Ping-Pong ball.

The system-based approach can be recycled ones more. For example, the pulse transmitter in the ultrasonic sensor can be split into different blocks: the 40 kHz oscillator, the envelope generator, the
masking of the oscillator by the envelope and the driver for the loudspeaker. These different blocks are basic electronic building blocks that the students already studied or can be found easily in references on electronic circuits or on the internet.

When the different basic building blocks are combined, the students experience the concepts of loading and interference. The loading of a circuit requires the design of an output driver such that it matches the input characteristics of the next block. The interference is minimized by a careful routing of the power line, proper decoupling and filtering of the appropriate signals.

During this step, they learn to iteratively use the system-level approach to end up with a hierarchical design and how elementary building blocks in electronics or informatics can be combined into a subsystem that meets the specifications. They also experience that the basic building blocks seen in introductory courses are used in real systems.

![Figure 2. In the case of the ultrasonic height sensor, the block can be further split into three sub-blocks: the transmitter, the receiver and the signal processing.](image)

4.4.3.4 Step 4: Going back to the system level

Now that the separate blocks are operational, the challenge lies in their combination, i.e. by suppressing the interference and overcoming the loading of the different blocks.

Finally, system-level testing is performed. Once the system is reaching specs, it becomes time to close the control loop. Here, students encounter feedback loops for the first time. This shows them the power of feedback control and nicely illustrates the properties of the different control actions: The proportional gain which lacks accuracy, the derivative action for speed improvement and the integral action for error removal and the consequent instability.

First – by playing manually with the gains of the different actions – the students discover the advantages and disadvantages of the different actions. Second – by the end of the day – the students are explained how the relay test works. This allows them to obtain a working controller without any heuristic search.
Hence, the way is now opened for them to understand the usefulness and the power of the otherwise so abstract control theory. They learn to evaluate the control behaviour by looking at the tracking behaviour and the disturbance rejection.

During this step, they learn how to combine different blocks to a larger system and also to evaluate and tune the system’s performance by measurements.

To finalize their effort and tune their controller, they need one and a half day.

### 4.4.3.5 Step 5: Presentation

During the last half day, the groups have to demonstrate their system to the groups and give a scientific presentation of their solution. This presentation trains their communication skill. It also enables them to learn about other implementations from other groups.

### 4.4.3.6 Conclusion

The project is mainly intended to help the students to make an informative choice about their engineering specialization, and also teaches them a fundamental engineering concept: design a complex control system.

The system-level systematic framework enables the engineer to develop well-understood, high-quality, reproducible and reusable results.

### 4.5 COURSES LECTURED IN THE FACULTY OF SCIENCE AND BIO-ENGINEERING

<table>
<thead>
<tr>
<th>Lectures and practical courses</th>
<th>Credits</th>
</tr>
</thead>
</table>
| Berekenbaarheid en informatietheorie\(^5\) - Prof. L. Van Biesen  
Computation and Information Theory  
1\(^{st}\) Year Master of Sciences in Engineering: Computer Science (compulsory) | 6 |
| Geographical Information Systems - Prof. L. Van Biesen  
2\(^{nd}\) year Master of Ecological Marine Management (compulsory)  
2\(^{nd}\) Year Master of Sciences in Engineering: Applied Computer Science (optional)  
2\(^{nd}\) Year Master of Science Ecological Marine Management (compulsory) | 3 |
| Theory of Computation and Information Theory - Prof. L. Van Biesen  
1\(^{st}\) Year Master of Sciences in Engineering: Computer Science (compulsory) | 6 |
| Analyse, WPO\(^6\): Dr. Anna Marconato and Dr. Mariya Ishteva  
Analysis, Exercises  
1\(^{st}\) Year Bachelor of Science in Engineering | 14 |
| Complexe Analyse, WPO\(^7\): Dr. Jan Goos  
Complex Analysis, Exercises,  
2\(^{nd}\) Year Bachelor of Sciences in Engineering and physics | 5 |

\(^5\) The language of tuition of this course is Dutch  
\(^6\) The language of tuition of this course is Dutch  
\(^7\) The language of tuition of this course is Dutch
4.6 NATIONAL AND INTERNATIONAL COURSES

4.6.1 National courses (since 2003):

4.6.1.1 Identificatie van systemen (Identification of Systems)

Organised by: University of Gent, “Instituut voor permanente vorming”
Location: IVPV - UGent, Technologiepark, 9052 Gent-Zwijnaarde
Lectured by: Johan Schoukens and Yves Rolain
Dates: 7, 14 and 21 December 2004

Meten en modelleren is een basisactiviteit van vele ingenieurs: modellen worden gebruikt tijdens het ontwerp, in simulatoren en in eindproducten. Het modelleringsproces is een complexe activiteit die in 4 grote delen kan worden opgesplitst: verzamelen van de experimentele data; opstellen van een model; in overeenstemming brengen van een model en data; validatie van de resultaten. Systeemidentificatie biedt een systematische, optimale oplossing en wordt in deze module bestudeerd, met als toepassing de identificeren van dynamische systemen. Hierbij wordt de klemtoon gelegd op het aanbrengen van de ideeën, ondersteund door uitgewerkte Matlab illustraties.

De behandelde topics zijn

- Systeemidentificatie: wat? waarom?
  Een verhelderend voorbeeld
  Goede schatters/slechte schatters, wat mag je ervan verwachten?

- Niet-parametrische identificatie van frequentieresponse functies
  Basisidee: van tijdsignaal tot frequentierespons (FRF)
  Experiment design: keuze van de excitatiesignalen, ruisgevoeligheid, uitmiddelen
  Nietlineaire distorties: detectie, kwalificatie en quantificatie

- Parametrische identificatie van de transferfunctie
  Basisidee: van data tot model
  Tijdsdomein- en frequentiedomein-identificatie

- Identificatie van tijdsvariërende systemen
  Basisidee
  Balans volgsnelheid/ruisgevoeligheid

4.6.1.2 Courses lectured at the Katholieke Universiteit Leuven (KUL)

- Rik Pintelon: “Identificeren van lineaire dynamische systemen” 18 HOC, 36 WPO (4 credits): keuze o.o. in de Master in de wiskundige ingenieurstechnieken
- Johan Schoukens: “Systeemidentificatie en modellering” (6 credits):
- Master in de ingenieurswetenschappen: wiskundige ingenieurstechnieken
- Master in de ingenieurswetenschappen: bouwkunde
- Master in de wiskunde
• Master in de ingenieurswetenschappen: wiskundige ingenieurstechnieken, programma voor industriële ingenieurs of master industriële wetenschappen (aanverwante richting) (na toeelating)

• Yves Rolain: “Meten en modelleren” keuze o.o. in de Master in de wiskundige ingenieurstechnieken

4.6.1.3 Open course program-IMEC academy: DSP concept explained with well-chosen exercises.

Organised by: imec-leuven
Location: imec, Leuven, Belgium
Lectured by: Johan Schoukens and Yves Rolain
Dates: November 14th, 28th, December 5th, 19th, 22nd (2011)

The course is a basic theoretical introduction to the concepts of digital signal processing.

• Introduction to system theory and signal processing impulse response and transfer functions of linear systems; stability-causality; poles and zeros; sampling DFF=FFT – all with Matlab exercises.

• Introduction to measurement and modelling of linear systems (measurement of the frequency response function; choice of excitation; the effect of noise and leakage; estimation of the parametric model) – including Matlab exercises.

• Handling non-linear distortion: detection; classification and qualification of linear distortion – including Matlab exercises.

• Design of digital filters and systems (basic choices and non idealities: filter examples; compression and expansion ...) – including Matlab exercises.

• Wrap-up: further Matlab exercises applying the techniques on integrated problems. Analysis of implemented filters; evaluating non-linear distortions (impact of quantizing noise).

4.6.1.4 Measuring, Modeling Identification and design of (non)linear systems

Organised by: imec-leuven
Location: NXP Semiconductors, Nijmegen, The Netherlands
Lectured by: Johan Schoukens, Gerd Vandersteen and Yves Rolain
Dates: April 9-12, June 12-14 (2013)

4.6.2 International courses (since 2003):

4.6.2.1 Characterisation of Multiport Systems through 3-port LSNA Measurements

Location: Seminar at NIST, Boulder, CO, December 2003
Lectured by: Wendy Van Moer
# attendees: 20
4.6.2.2 The use of multisines

Location: Seminar at NIST, Boulder, CO, December 2003
Lectured by: Daan Rabijns
# attendees: 20

4.6.2.3 GIS training in SEAFDEC, Thailand

Location: Samut Prakan SEAFDEC/Training Department, Thailand, Bangkok, 2005
Lectured by: Tesfazghi Ghebre Egziabeher

The theme of the course was interrelated to the use of Geographic Information System for Fishery Management. Participants of the course were members of the Southeast Asian Fisheries Development and Training Centre (SEAFDC/TD), who were professionally engaged in the fishing industry.

4.6.2.4 Measuring, Modeling, and Designing in a Nonlinear Environment

Location: tutorial workshop organized at I2MTC08, Vancouver, Canada, May 2008
Lectured by: Yves Rolain, Ludwig De Locht, Rik Pintelon, Johan Schoukens, Wendy Van Moer

Topics:

- Best linear approximation and design: A perfect marriage (L. De Locht)
- Measurement of the Best Linear Approximation of Nonlinear Systems (W. Van Moer)
- Impact of nonlinear distortions on the linear framework (J. Schoukens)
- Frequency Response Function Measurement in the Presence of Nonlinear Distortions (R. Pintelon)

4.6.2.5 VUB - doctoral school on Identification of Nonlinear Dynamic Systems

Location: Dept. ELEC, Vrije Universiteit Brussel, Building K, 6th floor
Lectured by: Rik Pintelon, Johan Schoukens, Gerd Vandersteen, Yves Rolain
# attendees: 18 (8 different nationalities) in 2008, 16 (5 different nationalities) in 2009, 14 (9 different nationalities) in 2010, 18 (9 different nationalities) in 2011, 20 (12 different nationalities) in 2012 , 24 (8 different nationalities) in 2013 and 25 (9 different nationalities) in 2014.

The department ELEC of the VUB, organized a 4 weeks doctoral school (from the 26th of May till the 20th of June in 2008; from 16th May till the 21st of June in 2009; from the 6th of June till the 2nd of July in 2010; from 7th of May until 5th of June in 2011; from 20th of May until 14th of June in 2012; from 12th May until 8th of June in 2013 and from 11th May until 7th June in 2014) to give an intensive training on advanced modelling and simulation techniques of (non)linear dynamic systems, starting from experimental data. Half of the time has been spent on courses/exercises, the other half on a project to get hands-on experience. The material taught during the courses and exercises has been put into practice during a clearly defined project, in order to get hands-on experience. The course covered the following topics:

- A basic introduction to system identification,
- Identification of dynamic systems,
• Measuring and modelling of nonlinear systems,
• Simulation tools for nonlinear systems,
• Design and characterization of high-frequency (nonlinear) systems (optional: intended for those with an interest in microwave systems).

The next doctoral school on Identification of Nonlinear Dynamic Systems® will be organised in May/June 2015 (from the 18th of May 2015 till the 12th of June 2015). Participation to this workshop offers a number of advantages. Besides the training, it can also be the start of a collaboration. To some of the participants we can offer a one year grants to start a research collaboration, or even a full four years grant for a (joint) PhD.

Interested candidates are invited to send their curriculum vitae, together with a short motivation why they would like to follow this course, and this before the 20th of February 2015. They can also express their interest in the possibility for a longer cooperation. Please do not hesitate to contact us if you would like to have more information: email: info@elecdoctoralschool.be.

4.6.2.6 **Mini-course on System identification in the behavioral setting: A low-rank approximation approach**


*Lectured by:* Ivan Markovsky

4.6.2.7 **SOCN course Low-rank approximation and its applications,**

*Dates and location:* March 12, 13, 14, 19, 20, 21, 2014, K.U.Leuven, 20 attendees

*Lectured by:* Ivan Markovsky

**Description**

Established data modeling approaches are often derived in a stochastic setting. An alternative deterministic approximation approach, known in the systems and control literature as the behavioral approach, has been developed since the 80’s by Jan C. Willems and co-workers. The behavioral approach differentiates between the abstract notion of a model and the concrete notion of a model representation. This distinction proves to be important for developing a coherent theory and effective algorithms for system identification, analysis, and control. The course presents a behavioral approach to system identification.

The highlight of the course is the low-rank approximation problem, which is a practical tool for modeling in the behavioral setting. A matrix constructed from the data being rank deficient implies that there is an exact low complexity linear model for that data. Moreover, the rank of the data matrix corresponds to the complexity of the model. In the generic case when an exact low-complexity model

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http://www.elecdoctoralschool.be
does not exist, the aim is to find a model that fits the data approximately. The corresponding computational problem is low-rank approximation. In the case of linear time-invariant dynamical models, the data matrix is, in addition, Hankel structured and the approximation should have the same structure.

Once the approximate system identification problem is formulated as a low-rank approximation problem, it is solved by generic methods. Except for a few special cases, however, low-rank approximation problems are nonconvex and a global solution is expensive to compute. In the course, we present methods based on local optimization, which lead to fast and effective algorithms. The cost function evaluation has the system theoretic interpretation of Kalman smoothing.

In addition to the theory and algorithms for exact and approximate system identification, the course presents examples from system theory (model reduction and distance to uncontrollability), computer algebra (approximate common divisor computation), and machine learning (recommender systems). Software implementation of the developed methods makes the theory applicable in practice. An essential part of the course are exercises, which give hands-on experience with the presented theory and methods.

4.6.2.8 Nonlinear Distortion analysis of circuits and systems

Date and location: tutorial workshop organized at ISCAS2014, Melbourne, Australia, 1/6/2014

Lectured by: Gerd Vandersteen and Adam Cooman

Attendees: 16

Description:

This tutorial aims to demystify the nonlinear distortion analysis of circuits and systems. Combining capability of analyzing large circuits through simulation-based methods and the analytical insight provided by symbolic methods enables the analysis of the nonlinear behavior of complex systems. The simulation-based methods make it possible to pinpoint the dominant nonlinearities, while the symbolic method can be used afterwards to get an analytical insight in the nonlinear behavior. This will be demonstrated using a large set of practical examples. The tutorial first introduces the necessary notions on Volterra theory, starting from classical linear system theory. The analytical expressions provided by Volterra result in a better understanding of the behavior of the system. The complexity of the resulting expressions, however, limits this technique to simple systems. Second, the tutorial introduces the Best-Linear-Approximation (BLA) paradigm, which represents the nonlinear system as a linear transfer function and additive nonlinear distortion components. It enables the separation of the various linear and nonlinear contributions and is able to pinpoint the dominant nonlinear distortions in a complex system and this in a hierarchical way. The main drawback of the simulation-based methods is, however, the reduced analytical insight. Finally, the power of both methods is illustrated on applications. Starting from a single-transistor circuit (a common source amplifier), the circuits’ complexity gradually increases over OPAMPs (different topologies), sigma-delta modulators and a receiver architecture. Both the symbolic method and the simulation-based methods are used side-by-side to gain insight in the nonlinear distortion properties of the system. All results are finally cross-checked and compared with publication results available in the literature.
5. Bibliography

5.1 BOOKS

b1. Identification of Linear Systems: A Practical Guideline to Accurate Modeling
J. Schoukens, R. Pintelon
The book is concentrated on the problem of accurate modelling of linear time invariant systems. These models can be continuous time (Laplace-domain) or discrete time (Z-domain). The complete experimental procedure is discussed: how to create optimal experiments (optimization of excitation signals), how to estimate the model parameters from the measurements, how to select between different models, etc. These problems are thoroughly discussed in the first section of the book. A profound theoretical development of the proposed identification algorithm is also made in this section. The second part consists of detailed illustrations of the proposed algorithms on practical problems: modelling an electronic, electrical, acoustic, mechanical system. Finally the book is completed with a practical guideline to help the user making the correct choices.
The book is intended for all those dealing with “practical” modelling problems and have to combine measurements and theory. A second group of interested people are those involved with identification theory.

b2. System Identification: A Frequency Domain Approach
Rik Pintelon, Johan Schoukens
How does one model a linear dynamic system from noisy data? This book presents a general approach to this problem, with both practical examples and theoretical discussions that give the reader a sound understanding of the subject and of the pitfalls that might occur on the road from raw data to validated model. The emphasis is on robust methods that can be used with a minimum of user interaction.
System Identification: A Frequency Domain Approach is written for practising engineers and scientists who do not want to delve into mathematical details of proofs. Also, it is written for researchers who wish to learn more about the theoretical aspects of the proofs. Several of the introductory chapters are suitable for undergraduates. Each chapter begins with an abstract and ends with exercises, and examples are given throughout.

b3. Exact and Approximate Modeling of Linear Systems: A Behavioral Approach
Ivan Markovsky, Jan C. Willems, Sabine Van Huffel, Bart De Moor
Society for Industrial and Applied Mathematics, 2006
Exact and Approximate Modeling of Linear Systems: A Behavioral Approach elegantly introduces the behavioral approach to mathematical modeling, an approach that requires models to be viewed as sets of possible outcomes rather than to be a priori bound to particular representations. The authors discuss exact and approximate fitting of data by linear, bilinear, and quadratic static models and linear dynamic models, a formulation that enables readers to select the most suitable representation for a particular purpose. This book presents exact subspace-type and approximate optimization-based identification methods, as well as representation-free problem formulations, an overview of solution approaches, and software implementation. Readers will find an exposition of a wide variety of modeling problems starting from observed data. The presented theory leads to algorithms that are implemented in C language and in MATLAB.

Rik Pintelon, Johan Schoukens
Systems identification is a general term used to describe mathematical tools and algorithms that build dynamical models from measured data. Used for prediction, control, physical interpretation, and the design of any electrical systems, they are vital in the fields of electrical, mechanical, civil, and chemical engineering. Focusing mainly on frequency domain techniques, System Identification: A Frequency Domain Approach, Second Edition also studies in detail the similarities and differences with the classical time domain approach. It highlights many of the important steps in the identification process, points out the possible pitfalls to the reader, and illustrates the powerful tools that are available.
Readers of this Second Edition will benefit from:
- Matlab® software support for identifying multivariable systems that is freely available at the website http://booksupport.wiley.com
- State-of-the-art system identification methods for both time and frequency domain data
- New chapters on non-parametric and parametric transfer function modeling using (non-)period excitations
- Numerous examples and figures that facilitate the learning process
- A simple writing style that allows the reader to learn more about the theoretical aspects of the proofs and algorithms

9 More publications of the department ELEC can be found on:
or http://wwwtw.vub.ac.be/elec/Papers%20on%20web/index.html
Unlike other books in this field, System Identification: A Frequency Domain Approach, Second Edition is ideal for practicing engineers, scientists, researchers, and both master's and PhD students in electrical, mechanical, civil, and chemical engineering.

b5. **Substrate Noise Coupling in Analog/RF Circuits**

Stephane Bronckers, Geert Van Der Plas, Gerd Vandersteen, Yves Rolain

Substrate noise coupling - the coupling of signals from one node to another via a substrate - is a frequent problem that occurs in integrated circuits. It is critical that today's engineers address this issue and this book shows them how. The book offers detailed guidance on the impact of substrate noise on a wide range of circuits operating from baseband frequencies up to mm-wave frequencies. This unique reference presents case studies to illustrate that careful modeling of the assembly characteristics and layout details is required to bring simulations and measurements into agreement. Practitioners learn how to use a proper combination of isolation structures and circuit techniques to make analog/RF circuits more immune to substrate noise.

b6. **Low Rank Approximation: Algorithms, Implementation, Applications.**

Ivan Markovsky


Matrix low-rank approximation is intimately related to data modelling; a problem that arises frequently in many different fields. Low Rank Approximation: Algorithms, Implementation, Applications is a comprehensive exposition of the theory, algorithms, and applications of structured low-rank approximation. Local optimization methods and effective suboptimal convex relaxations for Toeplitz, Hankel, and Sylvester structured problems are presented. A major part of the text is devoted to application of the theory. Applications described include:
- system and control theory: approximate realization, model reduction, output error, and errors-in-variables identification;
- signal processing: harmonic retrieval, sum-of-damped exponentials, finite impulse response modeling, and array processing;
- machine learning: multidimensional scaling and recommender system;
- computer vision: algebraic curve fitting and fundamental matrix estimation;
- bioinformatics for microarray data analysis;
- chemometrics for multivariate calibration;
- psychometrics for factor analysis; and
- computer algebra for approximate common divisor computation.

b7. **Mastering System Identification in 100 Exercises**

Johan Schoukens, Rik Pintelon, Yves Rolain


Systems identification is a general term used to describe mathematical tools and algorithms that build dynamical models from measured data. Mastering System Identification in 100 Exercises takes readers step by step through a series of MATLAB® exercises that teach how to measure and model linear dynamic systems in the presence of nonlinear distortions from a practical point of view. Each exercise is followed by a short discussion illustrating what lessons can be learned by the reader.

The book, with its learn-by-doing approach, also includes:
- State-of-the-art system identification methods, with both time and frequency domain system identification methods - including the pros and cons of each
- Simple writing style with numerous examples and figures
- Downloadable author-programmed MATLAB® files for each exercise--with detailed solutions
- Larger projects that serve as potential assignments

Covering both classic and recent measurement and identifying methods, this book will appeal to practicing engineers, scientists, and researchers, as well as master's and PhD students in electrical, mechanical, civil, and chemical engineering.

5.2 **CHAPTER IN BOOKS (2014)**

ch31. **Rank constrained optimization problems in computer vision**

I. Markovsky


A matrix constructed from exact data is rank deficient. The corresponding data fitting problem in the case of noisy data is a rank constraint optimization problem. In general, rank constraint optimization is a hard nonconvex problem, for which application specific heuristics are proposed. In the chapter, I do not describe solution methods for rank constraint optimization but refer the reader to the literature. Our main contribution is the analytic solution of contour alignment problem presented in Section 1.5.1. This problem is also nonconvex in the original problem variables, however, a nonlinear change of variables, renders the problem convex in the transformed variables. The link to low-rank approximation (the motto of the chapter) is presented in Section 1.5.4, where the problem is shown to be equivalent to the orthogonal Procrustes problem, which is a constrained low-rank approximation problem [12].

ch32. **Nonlinearly structured low-rank approximation.**

I. Markovsky and K. Usevich

Chapter 6 in "Low-Rank and Sparse Modeling for Visual Analysis". Springer, 2014. Yun Raymond Fu, editor

Polynomially structured low-rank approximation problems occur in algebraic curve fitting, conic section fitting, subspace clustering (generalized principal component analysis), and nonlinear and parameter-varying system identification. The
maximum likelihood estimation principle applied to these nonlinear models leads to nonconvex optimization problems and yields inconsistent estimators in the errors-in-variables (measurement errors) setting. We propose a computationally cheap and statistically consistent estimator based on a bias correction procedure, called adjusted least-squares estimation. The method is successfully used for cone section fitting and was recently generalized to algebraic curve fitting. The contribution of this book’s chapter is the application of the polynomially structured low-rank approximation problem and, in particular, the adjusted least-squares method to subspace clustering, nonlinear and parameter-varying system identification. The classical in system identification input-output notion of a dynamical model is replaced by the behavioral definition of a model as a set, represented by implicit nonlinear difference equations.

5.3 JOURNAL PAPERS (2014)

j479. Finding the dominant source of distortion in two-stage op-amps
Adam Cooman, Gerd Vandersteen, Yves Rolain
Although non-linear distortion is an important specification for op-amps, it is only determined at the end of the design in classical design flows, leaving the designers without a clue about its origin. Recently, the Best Linear Approximation (BLA) has been introduced to approximate non-linear systems. It allows to describe the behaviour of a non-linear system as a linear Frequency Response Function combined with a coloured noise source to describe respectively the wanted linear response and the distortion. To determine the dominant source of non-linear distortion, we combine the BLA with a classical noise analysis in this paper. The paper explains the BLA-based noise analysis and shows the result of this simulation-based analysis when applied to various op-amp architectures. The analysis pinpoints the non-linear hot-spots in an efficient way, without the use of special simulations, manual analytical calculations or modified transistor models.

j480. Software for weighted structured low-rank approximation
Ivan Markovsky and Konstantin Usevich
A software package is presented that computes locally optimal solutions to low-rank approximation problems with the following features: mosaic Hankel structure constraint on the approximating matrix, weighted 2-norm approximation criterion, fixed elements in the approximating matrix, missing elements in the data matrix, and linear constraints on an approximating matrix’s left kernel basis. It implements a variable projection type algorithm and allows the user to choose standard local optimization methods for the solution of the parameter optimization problem. For an m×n data matrix, with nm, the computational complexity of the cost function and derivative evaluation is O(m2n). The package is suitable for applications with nm. In statistical estimation and data modeling-the main application areas of the package-nm corresponds to modeling of large amount of data by a low-complexity model. Performance results on benchmark system identification problems from the database DAISY and approximate common divisor problems are presented.

j481. Measuring Nonlinear Effects in Respiratory Mechanics: A Proof of Concept for Prototype Device and Method
Clara M. Ionescu, Gerd Vandersteen, Johan Schoukens, Kristine Desager, Robin De Keyse
The forced oscillation technique (FOT) is a lung function test used in clinical practice to evaluate the respiratory impedance. One of the main advantages of FOT over other lung function tests is that it does not require any special breathing maneuvers from the subject, making it one of the simplest tests to evaluate respiratory mechanics. This paper describes the nonlinear effects in the respiratory signals and related measurement instrumentation during the FOT tests. First, this paper discusses some improvements made on a prototype FOT device to allow the generation of multisines below 4 Hz. Second, two methods are evaluated to detect the nonlinear effects: a robust method and a fast method. These methods allow a comparison of the nonlinear distortions in a prototype FOT device and a commercial FOT device. The nonlinear effects are also quantified using a new index definition. FOT lung function tests are performed to obtain two distinct data sets: 1) one mixed group of patients diagnosed with asthma and cystic fibrosis and 2) one group of healthy volunteers. With the extracted nonlinear contributions, a significant difference has been observed between the two groups. This delivers the proof of concept that low-frequency measurements of the respiratory mechanics are useful to evaluate lung pathologies.

j482. Smoothing the LPM-estimate of the frequency response function via an impulse response truncation technique.
M. Lumori, E. Geerardyn, J. Schoukens, J. Lataire
A statistical impulse response truncation technique is applied to the local polynomial method (LPM)-estimate of the frequency response function (FRF), resulting in an improved, smooth FRF. Formulated as a nonparametric linear-least-squares-estimate, the LPM is first applied to estimate the FRF from a full data record of a single-input-single-output system, systematically expressed in an output-error framework. The smooth characteristics of both the exact FRF and the leakage from transients allow for an optimal application of the local polynomial method, leading to the elimination of both the leakage and interpolation errors. The truncation method introduced in this paper makes it possible for the user to fine-tune the tradeoff between the uncertainty (variance) and the bias on the estimated instantaneous FRF.

j483. Heat transfer in a borehole heat exchanger: Frequency domain modeling
Griet Monteyne, Saqib Javed, Gerd Vandersteen
This paper proposes a new frequency domain method to model the heat transfer between the injected/extracted heat and the temperature of the fluid exiting a borehole heat exchanger. The method is based on in situ measurements and
focuses particularly on the short-term borehole heat transfer. It uses a rational function of the Warburg variable in the Laplace domain to model the borehole heat transfer. The rational model is transformed to a time domain model using inverse Laplace transformation. This time domain model makes it possible to calculate the temperature response on a random heat variation signal. The paper also demonstrates a new way to perform the classical thermal response test. Instead of injecting a constant amount of heat, the experiments have been performed using multiple short-duration heat injections. In this way, the obtained rational heat transfer model contains information about both the short- and the long-term heat transfer. The results obtained using the proposed modeling method are compared with those obtained from a state-of-the-art analytical method. The time domain model can be used to design a controller to optimize the performance of a Ground Source Heat Pump system, the efficiency of which depends strongly on the temperature of the fluid exiting the borehole.

**j484. Identification of Wiener-Hammerstein systems by a nonparametric separation of the best linear approximation**

Schoukens Maarten, Pintelon Rik, Rolain Yves

*Automatica*, February 2014, Vol. 50, No. 2, pp. 628 - 634

Wiener-Hammerstein models are flexible, well known and often studied. The main challenge in identifying a Wiener-Hammerstein model is to distinguish the linear time invariant (LTI) blocks at the front and the back. This paper presents a nonparametric approach to separate the front and back dynamics starting from the best linear approximation (BLA). Next, the nonparametric estimates of the LTI blocks in the model can be parametrized, taking into account a phase shift degeneration. Once the dynamics are known, the estimation of the static nonlinearity boils down to a simple linear least squares problem. The consistency of the proposed approach is discussed and the method is validated on the Wiener-Hammerstein benchmark that was presented at the IFAC SYSID conference in 2009.

**j485. Recent progress on variable projection methods for structured low-rank approximation**

Ivan Markovsky


Rank deficiency of a data matrix is equivalent to the existence of an exact linear model for the data. For the purpose of linear static modeling, the matrix is unstructured and the corresponding modeling problem is an approximation of the matrix by another matrix of a lower rank. In the context of linear time-invariant dynamic models, the appropriate data matrix is Hankel and the corresponding modeling problems becomes structured low-rank approximation. Low-rank approximation has applications in: system identification; signal processing, machine learning, and computer algebra, where different types of structure and constraints occur. This paper gives an overview of recent progress in efficient local optimization algorithms for solving weighted mosaic-Hankel structured low-rank approximation problems. In addition, the data matrix may have missing elements and elements may be specified as exact. The described algorithms are implemented in a publicly available software package. Their application to system identification, approximate common divisor, and data-driven simulation problems is described in this paper and is illustrated by reproducible simulation examples. As a data modeling paradigm the low-rank approximation setting is closely related to the the behavioral approach in systems and control, total least squares, errors-in-variables modeling, principal component analysis, and rank minimization.

**j486. A Fan-based, Low-frequent, Forced Oscillation Technique Apparatus**

Maes Hannes, Vandersteen Gerd, Muehlebach M., Jonescu Clara


The forced oscillation technique (FOT) is a noninvasive method to characterize the respiratory impedance (Z). Z is defined as the frequency-dependent ratio between pressure and flow. The FOT determines Z by superimposing small amplitude (in the order of 0.1 kPa) pressure oscillations on the normal breathing. It has been shown that a lot of useful information is contained in the frequency range of spontaneous breathing (0.1-1 Hz). In the current state-of-the-art methods, patient cooperation by means of voluntary apnea or mechanical ventilation is required to obtain the respiratory impedance at low frequencies. This article proposes a fan-based setup driven by a microcontroller. The setup allows to excite the respiratory mechanics at frequencies around the spontaneous breathing without requiring any patient effort. However, the (nonlinear) dynamic behavior of the setup and the pressure perturbations introduced by the subjects breathing jeopardize the spectral analysis of the measurement. Therefore, a combination of feedforward compensation of the excitation signal and linear feedback control are applied and discussed using measurements on a prototype device. A high-quality pressure signal is obtained, which makes it possible to obtain the respiratory impedance at low frequencies in a clinically practical way.

**j487. Bounded matrix factorization for recommender system**

Kannan, R. and Ishteva, M. and Park, H.


Matrix factorization has been widely utilized as a latent-factor model for solving the recommender system problem using collaborative filtering. For a recommender system, all the ratings in the rating matrix are bounded within a pre-determined range. In this paper, we propose a new improved matrix factorization approach for such a rating matrix, called (\(BMP\Full\)) (\(BMP\)) which imposes a lower and an upper bound on every estimated missing element of the rating matrix. We present an efficient algorithm to solve (\(BMP\)) based on the block coordinate descent method. We show that our algorithm is scalable for large matrices with missing elements on multi core systems with low memory. We present substantial experimental results illustrating that the proposed method outperforms the state of the art algorithms for recommender system such as Stochastic Gradient Descent, Alternating Least Squares with regularization, SVD++ and Bias-SVD on real world data sets such as Jester, Movielens, Book crossing, Online dating and Netflix.

**j488. Factorization approach to structured low-rank approximation with applications**

Mariya Ishteva, Konstantin Usevich, Ivan Markovsky


We consider the problem of approximating an affinely structured matrix, for example a Hankel matrix, by a low-rank matrix with the same structure. This problem occurs in system identification, signal processing and computer algebra, among others. We impose the low-rank by modeling the approximation as a product of two factors with reduced
A fractional approach to identify Wiener–Hammerstein systems
Laurent Vanbeylen

Block-oriented nonlinear models are appealing due to their simplicity and parsimony. Existing methods to identify the Wiener–Hammerstein model suffer from one or several drawbacks. This paper shows that it is possible to generate initial estimates in an alternative way. A fractional model parameterization is the key to the success of this approach. Advantages are that no more than two iterative optimizations are needed and that large model orders can be handled. As illustrated through a simulation example and experimental benchmark data, it gives superior initial estimates and comparable optimized results.

A Rigorous Analysis of Least Squares Sine Fitting Using Quantized Data: The Random Phase Case
P. Carbone, J. Schoukens


This paper considers least square (LS) based estimation of the amplitude and square amplitude of a quantized sine wave, done by considering random initial record phase. Using amplitude- and frequency-domain modeling techniques, it is shown that the estimator is inconsistent, biased, and has a variance that may be underestimated if the simple model of quantization is applied. The effects of both sine wave offset values and additive Gaussian noise are considered. General estimator properties are derived, without making simplifying assumptions on the role of the quantization process, to allow assessment of measurement uncertainty, when this LS procedure is used.

System-Level ESD Protection Design Using On-Wafer Characterization and Transient Simulations


A methodology for the design of circuits robust to system-level electrostatic discharge (ESD) stress is presented and verified with two case studies. The combination of on-wafer characterization and transient simulations enables the ESD designer to study the behavior of the component-level ESD protection design during system-level ESD stress with and without adding off-chip protection devices. The design of a system-level ESD protection solution can be verified long before IC packaging and even before the final system is built.

Improved Initialization for Nonlinear State-Space Modeling
A. Marconato, J. Sjöberg, J. Suykens and J. Schoukens


This paper discusses a novel initialization algorithm for the estimation of nonlinear state-space models. Good initial values for the model parameters are obtained by identifying separately the linear dynamics and the nonlinear terms in the model. In particular, the nonlinear dynamic problem is transformed into an approximate static formulation, and simple regression methods are applied to obtain the solution in a fast and efficient way. The proposed method is validated by means of two measurement examples: the Wiener-Hammerstein benchmark problem and the identification of a crystal detector.

A new modeling method for determining electrochemical parameters from LSV experiments using the stochastic noise. Part II: Experimental validation
L. Fernández Macía, R. Pintelon, A. Hubin


A novel modeling procedure to accurately determine the characteristic parameters of an electrochemical reaction from polarization curves, presented in the first part of this series, is validated now on voltammetry experiments. The combination of the local polynomial model and the analytical fitting allows determining the electrochemical parameters (rate constants, charge transfer coefficients, etc.) from one polarization curve. Linear sweep voltammetry coupled with rotating disk electrode is used to study two one-electron transfer reactions: the ferri/ferrocyanide reaction and the electroreduction of hexaamminecobalt(III). This approach enables the assessment of the quality of the modeling and the analysis of the influence of the experimental variations on the calculated parameters.

Fractional frequency domain identification of NaCl-glucose solutions at physiological levels
OLARTE RODRIGUEZ Oscar Javier, BARBÉ Kurt, VAN MOER Wendy, VAN INGELGEM Yves

Measurement, April 2014, Vo. 50, pp. 213 - 221

Electrical impedance spectroscopy (EIS) has been used to characterize different biological materials. This article exposes a methodology oriented to estimate glucose levels of a solution based on a rational fractional parametric model of the impedance data. The methodology is applied over saline-glucose solutions at five physiological glucose levels, using three sensors and five repetitions for each glucose concentration and employed sensor. The results suggest that changes in the glucose concentration produce significant changes in the impedance that should be reflected in the parametric model. The modeling procedure shows that the poles and zeros of an integer model presents a degree of correlation. However,
the correlation is clearly explicit employing fractional models where the mean location of the complex zeros is highly related to the glucose content in the sample.

**j495. Logistic ordinal regression for the calibration of oscillometric blood pressure monitors**
Barbé Kurt, Yuriy Kurylyak and Francesco Lamonaca
Oscillometric blood pressure (BP) monitors are omnipresent and used on a daily basis for personalized healthcare. Nevertheless, physicians generally approach these devices cautiously since the mercury Korotkoff sphygmomanometer remains the golden standard. Various reasons explain the hesitating attitude of the medical world towards automated BP monitors: (i) its principle is based on the pressure pulsations arriving at the cuff by the cardiac cycle instead of an audio waveform used by physicians triggered by the turbulences in the artery, (ii) the actual computation of the systolic and diastolic BP from the measured oscillometry is manufacturer dependent and not based on general scientific principles, (iii) the quality of the oscillometric monitors is labeled by a trial such that the devices correspond well to the Korotkoff method for the average healthy patient but deviates for patients suffering from hypo- or hypertension. In this paper, we develop a statistical learning technique to calibrate and correct an oscillometric monitor such that the device better corresponds to the Korotkoff method regardless of the health status of the patient. The technique is based on logistic regression which allows correcting and eliminating systematic errors caused by patients suffering from hyper- or hypotension. No user interaction is required since the technique is able to train and validate the calibration procedure in an unsupervised way. In our case study, the systematic error is reduced by nearly 50% corresponding to the performance specifications of the device.

**j496. Realization and identification of autonomous linear periodically time-varying systems**
I. Markovsky and J. Goos and K. Usevich and R. Pintelon
Automatica (50) 2014, pp. 1632-1640
Subsampling of a linear periodically time-varying system results in a collection of linear time-invariant systems with common poles. This key fact, known as "lifting", is used in a two step realization of the time-invariant dynamics (the lifted system). Computationally, this step is a rank-revealing factorization of a block-Hankel matrix. The second step derives a state space representation of the periodic time-varying system. It is shown that no extra computations are required in the second step. The computational complexity of the overall method is therefore equal to the complexity for the realization of the lifted system. A modification of the realization method is proposed, which makes the complexity independent of the parameter variation period. Replacing the rank-revealing factorization in the realization algorithm by structured low-rank approximation yields a maximum likelihood identification method. Existing methods for structured low-rank approximation are used to identify efficiently linear periodically time-varying system. These methods can deal with missing data.

**j497. Quantifying the Time-Variation in FRF Measurements Using Random Phase Multisines With Nonuniformly Spaced Harmonics**
Rik Pintelon, Ebrahim Louarroudi, John Lataire
Recently methods have been developed to detect and quantify the influence of time-variation in frequency response function measurements using random excitations. These methods can also be applied to random phase multisine excitations, provided uniformly spaced excited harmonics. However, in quite a few applications, a nonuniform harmonic spacing is required, for example, a quasi-logarithmic spacing to cover a large frequency range, and a random spacing to detect and quantify nonlinear distortions. Therefore, in this paper, the results are extended to random phase multisines with nonuniformly spaced harmonics. An in-depth study of the noise sensitivity (bias and variance) of the proposed procedure is made.

**j498. Accurate frequency domain measurement of the best linear time-invariant approximation of linear time-periodic systems including the quantification of the time-periodic distortions**
E. Louarroudi, R. Pintelon and J. Lataire
Mechanical systems and signal processing, 48 (2014), pp 274-299
Time-periodic (TP) phenomena occurring, for instance, in wind turbines, helicopters, anisotropic shaft-bearing systems, and cardiovascular/respiratory systems, are often not addressed when classical frequency response function (FRF) measurements are performed. As the traditional FRF concept is based on the linear time-invariant (LTI) system theory, it is only approximately valid for systems with varying dynamics. Accordingly, the quantification of any deviation from this ideal LTI framework is more than welcome. The Omeasure of deviationO allows us to define the notion of the best LTI (BLTI) approximation, which yields the best - in mean square sense - LTI description of a linear time-periodic LTP system. By taking into consideration the TP effects, it is shown in this paper that the variability of the BLTI measurement can be reduced significantly compared with that of classical FRF estimators. From a single experiment, the proposed identification methods can handle (non-)linear time-periodic ([N]LTP) systems in open-loop with a quantification of (i) the noise and/or the NL distortions, (ii) the TP distortions and (iii) the transient (leakage) errors. Besides, a geometrical interpretation of the BLTI approximation is provided, leading to a framework called vector FRF analysis. The theory presented is supported by numerical simulations as well as real measurements mimicking the well-known mechanical Mathieu oscillator.

**j499. Optimization on a Grassmann manifold with application to system identification**
K. Usevich and I. Markovsky
Automatica, Vol. 50, No. 6, June 2014, Pages 1656-1662
In this paper, we consider the problem of optimization of a cost function on a Grassmann manifold. This problem appears in system identification in the behavioral setting, which is a structured low-rank approximation problem. We develop a
new method for local optimization on the Grassmann manifold with switching coordinate charts. This method reduces the optimization problem on the manifold to an optimization problem in a bounded domain of an Euclidean space. Our experiments show that this method is competitive with state-of-the-art retraction-based methods. Compared to retraction-based methods, the proposed method allows to incorporate easily an arbitrary optimization method for solving the optimization subproblem in the Euclidean space.

j500. Frequency domain sample maximum likelihood estimation for spatially dependent parameter estimation in PDEs
van Berkel, M., G. Vandersteen, E. Geerardyn, R. Pintelon, H. Zwart, and M. De Baar
Automatica, Vol. 50, No. 8, August 2014, Pages 2113-2119
The identification of the spatially dependent parameters in Partial Differential Equations (PDEs) is important in both physics and control problems. A methodology is presented to identify spatially dependent parameters from spatio-temporal measurements. Local non-rational transfer functions are derived based on three local measurements allowing for a local estimate of the parameters. A sample Maximum Likelihood Estimator (SMLE) in the frequency domain is used, because it takes noise properties into account and allows for high accuracy consistent parameter estimation. Confidence bounds on the parameters are estimated based on the noise properties of the measurements. This method is successfully applied to the simulations of a finite difference model of a parabolic PDE with piecewise constant parameters.

j501. Frequency domain, parametric estimation of the evolution of the time-varying dynamics of periodically time-varying systems from noisy input-output observations
E. Louarroudi, J. Lataire, R. Pintelon, P. Janssens, J. Swevers
This paper presents a frequency domain, parametric identification method for continuous- and discrete-time, slow linear time-periodic (LTP) systems from input-output measurements. In this framework, the input as well as the input is allowed to be corrupted by stationary noise (i.e. an errors-in-variables approach is adopted). It is assumed that the system under consideration can be excited by a broad-band periodic signal with a user-defined amplitude spectrum (i.e. a multitone), and that the periodicity of the excitation signal TsysTsys can be synchronized with the periodicity of the time-varying TsysTsys (i.e. TsysTsys is also known as the pumping period). Once the parametric estimation of the time-evolution of the system parameters has been performed, the system model is evaluated at the level of the instantaneous transfer function (also known as system function, or parametric transfer function), which rigorously characterizes LTP systems. If the dynamics of the LTP system are slowly varying or the system is linear parameter varying (LPV), a frozen transfer function approach is provided to easily visualize and assess the quality of the estimated model. To give the estimated quantities a quality label, uncertainty bounds on the model-related quantities (such as the time-periodic (TP) system parameters, the frozen transfer function, the frozen resonance frequency, etc.) are derived in this paper as well. Besides, a clear distinction between the instantaneous and the frozen transfer function concept is made, and both can be estimated with the proposed identification scheme. The user decides which transfer function definition suits best its purpose in practice. Finally, the identification algorithm is applied to a simulation example and to real measurements on an extendible robot arm.

j502. Frequency-domain identification of time-varying systems for analysis and prediction of aeroselastic flutter
J. Ertveldt, J. Lataire, R. Pintelon, S. Vanlanduit
In this paper a different approach to wind tunnel flutter testing is presented. This procedure can now be performed as one continuous test, resulting in a major time saving. Both analysis of the current behaviour of the structure, and prediction towards higher velocities, are important for flight flutter testing, and are dealt with in this paper. The recently developed time-varying weighted non-linear least-squares estimator (TV-WNLS) (Lataire and Pintelon, 2011 [1]) is applied to the aeroselastic flutter problem. Smooth variation of the transfer function coefficients is forced through the TV-WNLS estimator, and the obtained polynomials are used as basis for predicting the damping ratio towards higher velocities. Selection of the model order is based on linear variation of the airspeed and the evaluation of Theodorsen’s unsteady aerodynamics for the frozen time-varying aeroselastic system at a certain constant velocity. Therefore, providing a physical justification for the extrapolation of the damping ratio towards higher velocities. The proposed method is applied to wind-tunnel measurements on a cantilevered wing. It is shown that the proposed method outperforms flutter speed prediction by classic damping ratio extrapolation and a non-parametric analysis of the time-varying signal.

j503. Identification of a nonlinear model for a glucoregulatory benchmark problem
Vanbeylen, L., A. Van Mulders, A. Abu-Rmileh
Biomedical Signal Processing and Control 13 (9), pp. 168-173
This paper presents a frequency domain, parametric identification method for a nonlinear dynamic model, called nonlinear Linear Fractional Representation (NL-LFR) model, that has been developed. The model, composed of a static nonlinearity (SNL) surrounded by linear dynamics, can account for both nonlinear feed-forward and nonlinear feed-back effects. Using two classical frequency response measurements, the SNL is automatically recovered in a user-friendly and efficient (non-iterative) way. In this contribution, the method is illustrated on a glucoregulatory benchmark dataset (insulin-glucose relationship of the human body). The research on insulin-glucose models is essential to develop methodologies to control the blood glucose level in diabetes patients. The obtained results outperform earlier results on the same benchmark data, while providing an excellent accuracy-complexity tradeoff.

j504. Time-frequency analysis of time-varying in vivo myocardial impedance
Benjamin Sanchez, Ebrahim Louarroudi, Rik Pintelon
Measurement 56, October 2014, pp. 19-29
The frequency response identification of a (bio-)system that is inherently nonlinear and time-varying, e.g. in vivo myocardial impedance, through electrical impedance spectroscopy (EIS) is still a task in progress today that deserves further research. In this work, the in-cycle time-varying behavior of in vivo myocardium is modeled by means of Fricke-MorseOs circuit model. Temporal changes in the in vivo myocardial impedance during the cardiac cycle provide valuable information on the heart physiological processes. The action potentials generated by the movement of ions through the
transmembrane ion channels in the cardiomyocytes produce the dominant time-periodic changes in a living heart. By performing then a time-based domain analysis, a periodic reconstruction of the experimental data is done and a periodically time-varying (PTV) electrical circuit model is extracted. Furthermore, it is shown that a limited number of harmonic components of the electrical circuit parameters, which corresponds to an integer number of the cardiac frequency, is sufficient to provide a realistic evolution of the myocardial frequency response over time. The root mean square error over time (RMSEoT) for the periodically reconstructed model is bounded to 1.7% and 0.20.2 degrees in the frequency band [100,103] kHz. Finally, based on the extracted PTV impedance model, we use the tool of harmonic impedance spectra (HIS) [1] and [2] to simulate and analyze in the bi-frequency domain the frequency response behavior of the in vivo myocardium during the cardiac cycle.

**j505. Interpolated modeling of LPV systems**
De Caigny, J., R. Pintelon, J. F. Camino, J. Swevers

This paper presents a new state-space model interpolation of local estimates technique to compute linear parameter-varying (LPV) models for parameter-dependent systems using a set of linear time-invariant models obtained for fixed operating conditions. The technique is based on observability and controllability properties and has three strong appeals, compared with the state of the art in the literature. First, it works for continuous-time as well as discrete-time multiple-input multiple-output systems depending on multiple scheduling parameters. Second, the technique is automatic to some extent, in the sense that, after the model selection, no user interaction is required at the different steps of the method. Third, the resulting interpolating LPV model is numerically well-conditioned such that it can be used for modern LPV control design. Moreover, the proposed technique guarantees that the local models have a coherent state-space representation encompassing existing results as a particular case. The benefits of the approach are demonstrated on a simulation example and on an experimental data set obtained from a vibroacoustic setup.

**j506. Measurement and characterization of glucose in NaCl aqueous solutions by electrochemical impedance spectroscopy**
Oscar Olarte, Kurt Barbé, Wendy Van Moer, Yves Van Ingelgem, Annick Hubin
Biomedical Signal Processing and Control, Vol. 14, November 2014, pp. 9-18

Electrochemical impedance spectroscopy (EIS) allows measuring the properties of the system as a function of the frequency as well as distinguishing between processes that could be involved: resistance, reactance, relaxation times, amplitudes, etc. Although it is possible to find related literature to in vitro and in vivo experiments to estimate glucose concentration, no clear information regarding the condition and precision of the measurements are easily available. This article first address the problem of the condition and precision of the measurements, as well as the effect of the glucose over the impedance spectra at some physiological (normal and pathological) levels. The significance of the measurements and the glucose effect over the impedance are assessment regarding the noise level of the system, the experimental error and the effect of using different sensors. Once the data measurements are analyzed the problem of the glucose estimation is addressed. A rational parametric model in the Laplace domain is proposed to track the glucose concentration. The electrochemical spectrum is measured employing odd random phase multisine excitation signals. This type of signals provides short acquisition time, broadband measurements and allows identifying the best linear approximation of the impedance as well as estimating the level of noise and non-linearities present in the system. All the experiments were repeated five times employing three different sensors from the same brand in order to estimate the significance of the experimental error, the effects of the sensors and the effect of the glucose over the impedance.

**j507. A recursive restricted total least-squares algorithm.**
S. Rhode, K. Usevich, I. Markovsky, and F. Gauterin

We show that the generalized total least squares (GTLS) problem with a singular noise covariance matrix is equivalent to the restricted total least squares (RTLS) problem and propose a recursive method for its numerical solution. The method is based on the generalized inverse iteration. The estimation error covariance matrix and the estimated augmented correction are also characterized and computed recursively. The algorithm is cheap to compute and is suitable for online implementation. Simulation results in least squares (LS), data least squares (DLS), total least squares (TLS), and RTLS noise scenarios show fast convergence of the parameter estimates to their optimal values obtained by corresponding batch algorithms.

**j508. Comparison of several data-driven non-linear system identification methods on a simplified glucoregulatory system example**
Anna Marconato, Maarten Schoukens, KoenTiels, Widadlage Dhammadk Widanage, Amjad Abu-Rmileh, Johan Schoukens
IET Control Theory and Applications, Vol. 8, No. 17, November 2014, pp. 1921-1930

In this study, several advanced data-driven non-linear identification techniques are compared on a specific problem: a simplified glucoregulatory system modelling example. This problem represents a challenge in the development of an artificial pancreas for Type 1 diabetes mellitus treatment, since for this application good non-linear models are needed to design accurate closed-loop controllers to regulate the glucose level in the blood. Block-oriented as well as state-space models are used to describe both the dynamics and the non-linear behaviour of the insulin–glucose system, and the advantages and drawbacks of each method are pointed out. The obtained non-linear models are accurate in simulating the patient’s behaviour, and some of them are also sufficiently simple to be considered in the implementation of a model-based controller to develop the artificial pancreas.

Maarten Schoukens, Gerd Vandersteen, Yves Rolain and Francesco Ferranti

This letter proposes a fast identification algorithm for Wiener-Hammerstein systems. The computational cost of separating the front and the back linear time-invariant block dynamics is significantly improved by using discrete optimization. The
discrete optimization is implemented as a genetic algorithm. Numerical results confirm the efficiency and accuracy of the proposed approach.

**j510. Wiener system identification with generalized orthonormal basis functions**
Koen Tiels, Johan Schoukens

*Automatica, Vol. 50, No. 12, pp. 3147-3154, 2014*

Many nonlinear systems can be described by a Wiener–Schetzen model. In this model, the linear dynamics are formulated in terms of orthonormal basis functions (OBFs). The nonlinearity is modeled by a multivariate polynomial. In general, an infinite number of OBFs are needed for an exact representation of the system. This paper considers the approximation of a Wiener system with finite-order infinite impulse response dynamics and a polynomial nonlinearity. We propose to use a limited number of generalized OBFs (GOBFs). The pole locations, needed to construct the GOBFs, are estimated via the best linear approximation of the system. The coefficients of the multivariate polynomial are determined with a linear regression. This paper provides a convergence analysis for the proposed identification scheme. It is shown that the estimated output converges in probability to the exact output. Fast convergence rates, in the order \( \mathcal{O}(NF - nrep/2) \), can be achieved, with \( NF \) the number of excited frequencies and \( nrep \) the number of repetitions of the GOBFs.

**j511. Variable projection for affinely structured low-rank approximation in weighted 2-norms**
K. Usevich and I. Markovsky

*Journal of Computational and Applied Mathematics, Vol. 272, pp. 430-448, 2014*

A software package is presented that computes locally optimal solutions to low-rank approximation problems with the following features: mosaic Hankel structure constraint on the approximating matrix, weighted 2-norm approximation criterion, fixed elements in the approximating matrix, missing elements in the data matrix, and linear constraints on an approximating matrix's left kernel basis. It implements a variable projection type algorithm and allows the user to choose standard local optimization methods for the solution of the parameter optimization problem. For an \( m \times n \) data matrix, with \( n \geq m \), the computational complexity of the cost function and derivative evaluation is \( O(m^2n) \). The package is suitable for applications with \( nm \). In statistical estimation and data modeling—the main application areas of the package—\( nm \) corresponds to modeling of large amounts of data by a low-complexity model. Performance results on benchmark system identification problems from the database DAISY and approximate common divisor problems are presented.

### 5.4 NATIONAL JOURNAL PAPER (2014)

**j75. Frequency Domain Modelling And Performance Optimisation Of Nonlinear Systems**
David Rijlaarsdam, Pieter Nuij, Maarten Steinbuch, Johan Schoukens

*Mikoniek, No. 4, 2014*

Concluding a series of three, this article deals with frequency domain methods when applied to systems subject to nonlinear dynamical effects. To meet increasing system requirements, techniques have to deal with the performance-degrading effects of nonlinearities. When applied with care, frequency domain methods provide practically applicable tools to model and optimise the performance of nonlinear systems. This article provides a brief overview and experimental examples of existing modelling techniques, as well as a novel method for performance assessment and optimisation using frequency domain based tooling.

### 5.5 CONFERENCE PAPERS (2014)

**c916. Nonparametric analysis and nonlinear state-space identification: a benchmark example**
Van Mulders A., J. Schoukens and L. Vanbeylen

*Proceedings of the 32nd IMAC, A Conference and Exposition on Structural Dynamics, Orlando, FL, USA, 2-7 February 2014, pp. 203-214*

This paper deals with the identification of nonlinear models. Such models are particularly useful when a linear model cannot describe the system under test well enough. This is the case in the benchmark example considered here: it is a structure that consists of two facing clamped steel beams connected by a non-linearly behaving flexible element. In this paper, the final goal is to construct a nonlinear state-space model, but first, it is shown how to retrieve a lot of information via one (or few) multisine experiments. Via such excitation signals, one gets a quick impression of the linear system dynamics and the levels of even and odd nonlinearities. After this analysis, an attempt is made to model the system by means of nonlinear (polynomial) state-space models, ranging from a model without structure to a block-structured model.

**c917. Nonlinear black-box identification of a mechanical benchmark system**
Vanbeylen, L. and A. Van Mulders

*Proceedings of the 32nd IMAC, A Conference and Exposition on Structural Dynamics, Orlando, FL, USA, 2-7 February 2014, pp. 215-222*

When linear models cannot represent the system under test with sufficient accuracy, nonlinear models can be very useful. The model identified here on the benchmark system is a black-box nonlinear LFR (Linear Fractional Representation) model, consisting of MIMO linear dynamics and a SISO static nonlinear part. This model is capable of reproducing both nonlinear feed-forward and nonlinear feedback effects; it achieves a good accuracy-parsimony tradeoff. It will be identified from the best linear approximation estimated at two amplitude levels of the applied input force.
c918. Structural and Functional Changes Occuring During Growth of the Respiratory System Can Be Quantified and Classified
Clara M. Ionescu, Dana Copot, Hannes Maes, Gerd Vandersteen, Amélie Chevalier and Robin De Keyser
7th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2014), Angers, France, March 3-6, 2014, pp. 110-115
This paper describes how nonlinear effects in the respiratory signals captured by means of the forced oscillation technique (FOT) non-invasive lung function tests. The measurements are performed using a prototype device developed such that it overcomes the limitations present in commercial FOT devices and allows the generation of multisine signals below 4 Hz. The principle of sending detection lines in the frequency domain for characterizing odd and even nonlinear contributions from a nonlinear system are introduced briefly to the reader. Two detection methods are presented: a robust method based on multiple measurements and a fast method based on a single measurement. The ingenious combination of the device and the method allow to detect the nonlinear contributions in the respiratory signals: pressure and flow. The intrinsically present nonlinear effects are quantified by measuring of novel index and analyzed in two groups of healthy volunteers, aged 14 years and aged 17 years, respectively. The results we obtain suggest that the proposed device, method and index are a successful combination of lung function testing, signal processing and classification items.

c919. System Identification in a Real World
13th International Workshop on Advanced Motion Control (AMC), Yokohama, Japan, 14-16 March, 2014
In this paper we discuss how to identify a mathematical model for a (non)linear dynamic system starting from experimental data. In the initial step, the frequency response function is measured, together with the properties of the disturbing noise and the nonlinear distortions. This uses nonparametric preprocessing techniques that require very little user interaction. On the basis of this information, the user can decide on an objective basis, in an early phase of the modelling process, to use either a simple linear approximation framework, or to build a more involved nonlinear model. We discuss both options here: i) Identification of linear models in the presence of nonlinear distortions, including the generation of error bounds; and ii) Identification of a nonlinear model. For the latter, a double approach is proposed, using either unstructured nonlinear state space models, or highly structured block oriented nonlinear models. The paper is written from a users perspective.

c920. Adaptive Noise Tracking for Cognitive Radios under more realistic operation conditions
Lee Gonzales Fuentes, Kurt Barbé and Wendy Van Moer
Normal operation conditions of cognitive radio applications require signal processing techniques that can be executed in real time. One of the first steps is to sense the occupied or free frequency channels. Two major drawbacks in the current techniques are that they assume (i) the noise as white and (ii) the measured spectrum as time-invariant. In real world, the noise is (i) colored so it disturbs the signal unevenly and (ii) its spectrum changes over time. Hence, tracking the time-varying noise spectrum can become crucial to remove the noise contributions and enhance the estimate of the received signal. In this paper, we study an auto-regressive model to develop an adaptive noise tracking technique using a Kalman filter such that an extension of Boll's noise subtraction technique, designed for audio noise cancellation, becomes feasible when adjusted to cognitive radio scenarios. Simulation results show the performance of this technique.

c921. Glucose Characterization Based on Electrochemical Impedance Spectroscopy
Oscar Olarte, Kurt Barbé, Wendy Van Moer and Yves Van Ingelgem
In this paper an equivalent circuit model is employed in the characterization of the impedance measurements of saline solutions at physiological glucose concentrations. The impedance data are obtained using a three electrodes cell configuration since it allows measuring the potential accurately in the working electrode independently from the counter electrode. As excitation signal an odd random phase multisine is employed which allows identifying the best linear approximation, the noise level and the non-linear distortions present in the system. The results show a significant change in the impedance as a function of the glucose at the interphase electrode-electrolyte as well as in the bulk solution. This is an important step towards the development of glucose measurement systems based in electrochemical impedance spectroscopy (EIS).

c922. Monte-Carlo parameter uncertainty analysis under dynamical and operational measurement conditions
Kurt Barbé, Lee Gonzales-Fuentes, and Wendy Van Moer
For controlling, observing and optimizing engineering processes one needs often dedicated experiments. Unfortunately no measurement is exact such that deriving conclusions from a measurement is exact such that deriving conclusions from a measurement campaign requires some caution. Hence, in order to control or optimize a certain parameter of interest, the measurement uncertainty of the parameter needs to be quantified. In the literature two methods are proposed to perform this task: analysis of the noise propagation or Bootstrap Monte-Carlo (BMC) methods. The first one is inaccessible for the layman user. The BMC is difficult to perform if noise soures are mutually correlated since all correlations need to be taken into account. We present a new direct measurement for parameter uncertainty which can be operated under correlated noise sources without the need of explicit knowledge or description of the correlation at hand.
Data-Driven Signal Processing: A Low-rank approximations approach
I. Markovsky
Lecture at International Conference on Numerical Methods for Scientific Computations, Bansko, Bulgaria, May 19-22, pp. 82-83
State-of-the-art signal processing and control methods are model based and require a model identification step prior to solving the actual data processing problem. Starting with a review of classical system identification, this talk presents a model-free data processing approach, in which model parameters need not be explicitly estimated. The underlying computational tool in the new setting is low-rank approximation of a structured matrix constructed from the data. Preserving the structure in the approximation leads to statistically optimal estimators and fast computational methods.

Distortion Contribution Analysis by combining the Best Linear Approximation and noise analysis
Adam Cooman and Gerd Vandersteen
The non-linear performance of analogue electronic circuits is crucial during the design phase, while circuit simulators only give measures about the distortion generated by the total circuit, leaving designers clueless about the source of the problem. Distortion Contribution Analysis (DCA) is a simulation-based analysis technique that determines the distortion generated in the sub-circuits and shows their contribution to the total distortion of the circuit. DCA can be used to efficiently decrease the distortion generated by a circuit, because it points the designer to the origin of the problem. Recently, a DCA based on the Best Linear Approximation (BLA) has been introduced as alternative to the Volterra-based techniques. However, a major drawback of the current implementation of the BLA-based DCA is its limitation to single-input single-output (SISO) and single-input multiple-output (SIMO) cases. In this paper, we propose a model for the frequency response function of a circuit which includes multiple inputs and outputs (MIMO) and is based on the Best Linear Time-Invariant (BLTI) approximation. The resulting model is also valid for non-periodic scheduling and input signals.

Estimation of Linear Parameter-Varying affine state space models using synchronized periodic input and scheduling signals
Goos, J., J. Lataire, and R. Pintelon
Proceedings of the American Control Conference, Portland, Oregon (USA), June 4-6, 2014, pp. 3754 - 3759
During the past decades some very interesting results have been obtained in controller synthesis using Linear Parameter-Varying (LPV) systems. However, the LPV models are commonly required to be transformed into State Space (SS) form. We tackle the LPV SS identification problem directly in the frequency domain. To the best of our knowledge, this is a novel approach. When the input and scheduling are chosen to be periodic and synchronized, the state space equations are structured and sparse in the frequency domain. The parameters of these state space equations are estimated by minimizing a weighted non-linear least squares criterion. Starting values are generated via the Best Linear Time-Invariant (BLTI) approximation. The resulting model is also valid for non-periodic scheduling and input signals.

Evaluation of the number of PPG harmonics to assess Smartphone effectiveness
Giuseppe Polimeni, Alfonso Scarpino, Kurt Barbé, Francesco Lamonaca and Domenico Grimaldi
Smart technologies are increasing in popularity due to their current reduction in price and increased accessibility to the lay user. As a result, health monitoring for personalized healthcare is growing in importance. One problem for the current smart technologies is the poorer signal acquisition quality with respect to clinically validated devices. In this work, we evaluate the minimal required sampling frequency to acquire the Photoplethysmography (PPG) by means of a Smartphone such that the PPG features remain sufficiently accurate. In particular, we show that a sampling frequency of 30 frames per second of the Smartphone camera is sufficient to extract the PPG signal.

A novel t-test for low-SNR fMRI brain mapping
Kurt Barbé and Lieve Lauwers
Detecting signal in fMRI studies relies on the classical testing framework developed for Gaussian signals. Unfortunately, fMRI signals are amplitude measurements such that the signal follows a Rice distribution. The classical t-test used for detection performs reasonably well for signals with a high Signal-to-Noise Ratio (SNR). To accurately detect the voxels at the border of the brain region of interest, we need to deal with small SNRs such that dealing with the Rice distribution is a necessity. Most techniques dealing with the Rice distribution require amplitude estimates based on the Maximum Likelihood Estimate (MLE) requiring an iterative approach and may still lead to a false local solution. The analytical alternative to the MLE is by applying the Method-of-Moment (MoM) estimator which performs better for low SNR conditions than the Gaussian framework. In this paper, we propose a novel t-test based on the MoM-estimates for signal and noise power to assess voxel activity and to generate the according brain map.

The use of the harmonic median for fMRI signal intensity characterization
Lieve Lauwers and Kurt Barbé
The problem of detecting significant brain activity upon stimulus in functional Magnetic Resonance Imaging (fMRI) data is tackled by a statistical data analysis for which the signal’s amplitude is required. From literature, it is known that fMRI
data follow a Rice distribution. Hence, for fMRI signal detection first the parameters of the Rice distribution need to be estimated. Different methods exist and each has their own pros and cons. In this paper, a novel estimation approach is presented in order to overcome the drawbacks of the existing methods. The proposed estimator is based on the harmonic median. Its performance is verified via a simulation experiment and compared with the state-of-the-art approaches.

**c929. Identification of a block-structured model with several sources of nonlinearity**
Van Mulders, A., L. Vanbeylen and K. Usevich
European Control Conference, Strasbourg, France, June 24-27, 2014, pp. 1717 - 1722

This paper focuses on a state-space based approach for the identification of a rather general nonlinear block-structured model. The model has several Single-Input Single-Output (SISO) static polynomial nonlinearities connected to a Multiple-Input Multiple-Output (MIMO) dynamic part. The presented method is an extension and improvement of prior work, where at most two nonlinearities could be identified. The location of the nonlinearities or their relation to other parts of the model does not have to be known beforehand: the method is a black-box approach, in which no states, internal signals or structural properties need to be measured or known. The first step is to estimate a partly structured polynomial (nonlinear) state-space model from input-output measurements. Secondly, an algebraic approach is used to split the dynamics and the nonlinearities by decomposing the multivariate polynomial coefficients.

**c930. Identification method for nonlinear LFR block-oriented models with multiple inputs and outputs**
Vanbeylen, L. and A. Van Mulders
European Control Conference, Strasbourg, France, June 24-27, 2014, pp. 376 – 381

Recently, the nonlinear LFR model has been proposed as a candidate model with high potential, due to its surprising flexibility and parsimony. It is a quite general block-oriented model consisting of a static nonlinearity (SNL) and multiple-input-multiple-output (MIMO) dynamics. It can cope with both nonlinear feedforward and nonlinear feedback effects and does not postulate the SNL’s location prior to the identification. This contribution extends the model from single-input-single-output (SISO) to MIMO. Starting from two classical frequency response measurements of the system, the method delivers the best possible MIMO dynamics and estimates the SNL in an automated, user-friendly, non-iterative way, with an improved computational efficiency. The method is successfully applied on a numerical simulation example to illustrate the theory.

**c931. SVD truncation schemes for fixed-size kernel models**
Ricardo Castro, Siamak Mehrkanoon, Anna Marconato, Johan Schoukens, Johan Suykens

In this paper, two schemes for reducing the effective number of parameters are presented. To do this, different versions of Fixed-Size Kernel models based on Fixed-Size Least Squares Support Vector Machines (FS-LSSVM) are employed. The schemes include Fixed-Size Ordinary Least Squares (FS-OLS) and Fixed-Size Ridge Regression (FS-RR) with their respective truncations through Singular Value Decomposition (SVD). When these schemes are applied to the Silverbox and Wiener-Hammerstein data sets in system identification, it was found that a great deal of the complexity of the model could be reduced in a trade-off with the generalization performance.

**c932. Tensor low multilinear rank approximation by structured matrix low-rank approximation**
M. Ishteva and I. Markovsky

We present a new connection between higher-order tensors and affinely structured matrices, in the context of low-rank approximation. In particular, we show that the tensor low multilinear rank approximation problem can be reformulated as a structured matrix low-rank approximation, the latter being an extensively studied and well understood problem. We first consider symmetric tensors. Although the symmetric tensor problem is at least as difficult as the general unstructured tensor problem, the symmetry allows us to simplify the problem formulation and to clearly show its relation to the matrix structured low-rank approximation problem. By imposing linear equality constraints in the optimization problem, the proposed approach is applicable to unstructured tensors, as well as to affinely structured tensors. Therefore, it can be used to find (locally) optimal low multilinear rank approximation with a predefined structure.

**c933. Linking regularization and low-rank approximation for impulse response modelling**
Anna Marconato, Lennart Ljung, Yves Rolain, Johan Schoukens
Proceedings of 19th IFAC World Congress, Cape Town (South Africa), August 24-29, 2014, pp. In the last years, nonparametric linear dynamical systems modeling has regained attention in the system identification world. In particular, the application of regularization techniques that were already widely used in statistics and machine learning, has proven beneficial for the estimation of the impulse response of linear systems. The low-rank approximation of the impulse response obtained by the truncated singular value decomposition (SVD) also leads to reduced complexity estimates. In this paper, the link between regularization and SVD truncation for finite impulse response (FIR) model estimation is made explicit. The SVD truncation is reformulated as a regularization problem with a specific choice of the regularization matrix. Both approaches regularization and SVD truncation) are applied on a FIR modeling example and compared with the classic prediction error method/maximun likelihood approach. The results show the advantage of these techniques for impulse response estimation.

**c934. Enhancing H-Infinity Norm Estimation using Local LPM/LRM Modeling: Applied to an AVIS**
Egon Geerardyn, Tom Oomen, Johan Schoukens
Proceedings of 19th IFAC World Congress, Cape Town (South Africa), August 24-29, 2014
Accurate uncertainty modeling is of key importance in high performance robust control design. The aim of this paper is to develop a new uncertainty modeling procedure that leads to enhanced accuracy for the $H_{\infty}$ norm. A frequency response based approach is adopted. The key novelty of this paper is a new method to address the intergrid error using local parametric modeling methods. The local polynomial and rational models enhance the estimates at the discrete frequency grid. Moreover, the presented methods are shown to enhance the intergrid error estimate. This is illustrated using simulations and experiments on an industrial active vibration isolation system. Compared to the local polynomial models, local rational models are able to handle lightly-damped resonances using far fewer data points, which means that measurement time can be reduced significantly.

C935. Comparative study of two global affine Linear Periodic Parameter Varying State Space model estimation algorithms
Goos, J., and R. Pintelon
Proceedings of 19th IFAC World Congress, Cape Town (South Africa), August 24-29, 2014
A comparative study is made between two global Linear Periodic Parameter-Varying (LPPV) identification algorithms. The first method is a state-of-the-art subspace identification method in the time domain. The second is a newly developed frequency domain approach, where the identification experiment is designed carefully so we can exploit the resulting structure. For both methods, the result is a state space model with an affine dependence on the varying parameters, which can be used for LPV control synthesis. Simulations show that the frequency domain procedure has a lower variance for identical experimental conditions.

C936. Frequency-domain least-squares support vector machines to deal with correlated errors when identifying linear time-varying systems
John Lataire, Dario Piga, Roland Tóth
Proceedings of 19th IFAC World Congress, Cape Town (South Africa), August 24-29, 2014
A Least-Squares Support Vector Machine (LS-SVM) estimator, formulated in the frequency domain is proposed to identify linear time-varying dynamic systems. The LS-SVM aims at learning the structure of the time variation in a data driven way. The frequency domain is chosen for its superior robustness w.r.t. correlated errors for the calibration of the hyper parameters of the model. The time-domain and the frequency-domain implementations are compared on a simulation example to show the effectiveness of the proposed approach. It is demonstrated that the time-domain formulation is misleading during the calibration due to the fact that the noise on the estimation and calibration data sets are correlated. This is not the case for the frequency-domain implementation.

C937. Generating initial estimates for Wiener-Hammerstein systems using phase coupled multisines
Schoukens J., Tiels K., and Schoukens M.
Proceedings of 19th IFAC World Congress, Cape Town (South Africa), August 24-29, 2014
Block oriented nonlinear models capture the dynamics of a nonlinear system with linear dynamic sub-systems (L), the nonlinear behavior is modelled using static nonlinear sub-blocks (N). In this paper we study the generation of initial estimates for the linear dynamic blocks of a Wiener-Hammerstein system. For performing each identification experiment, it turns out to be very difficult to split the global dynamics over these individual blocks. In this paper a method is proposed that allows the poles of the best linear approximation to be assigned to the first or second linear block. Once this is done, it is shown in the literature that the remaining initialization problem can be solved much easier than the original one. The initial estimates of the transfer functions of the first and last dynamic block are estimated using a modified best linear approximation. The shifted poles and zeros result in a transfer function with complex coefficients that can be identified using a modified frequency domain estimation method. This results in a simple initialization method, based on a linear system identification step.

C938. Identification of parallel Wiener-Hammerstein systems with a decoupled static nonlinearity
Schoukens M., Tiels K., Ishteva M., and Schoukens J.
Proceedings of 19th IFAC World Congress, Cape Town (South Africa), August 24-29, 2014
Block-oriented models are often used to model nonlinear systems. This paper presents an identification method for parallel Wiener-Hammerstein systems, where the obtained model has a decoupled static nonlinear block. This decoupled nature makes the interpretation of the obtained model more easy. First a coupled parallel Wiener-Hammerstein model is estimated. Next, the static nonlinearity is decoupled using a tensor decomposition approach. Finally, the method is validated on real-world measurements using a custom built parallel Wiener-Hammerstein test system.

C939. Generation of initial estimates for Wiener-Hammerstein models via basis function expansions
Tiels K., Schoukens M., and Schoukens J.
Proceedings of 19th IFAC World Congress, Cape Town (South Africa), August 24-29, 2014, pp. 114
Block-oriented models are often used to model nonlinear systems. They consist of linear dynamic (L) and nonlinear static (N) sub-blocks. This paper proposes a method to generate initial values for a Wiener-Hammerstein model (LNL cascade). The method starts from the best linear approximation (BLA) of the system, which provides an estimate of the product of the transfer functions of the two linear dynamic sub-blocks. Next, the poles of the BLA are assigned to both linear dynamic sub-blocks. The linear dynamics are then parameterized in terms of rational orthonormal basis functions, while the nonlinear sub-block is parameterized by a polynomial. This allows us to reformulate the model to the cascade of a parallel Wiener (with parallel LN structure) and a linear dynamic system, which is bilinear in its parameters. After a bilinear optimization, the parallel Wiener part is projected to a single-branch Wiener model. The approach is illustrated on a simulation example.
Estimation of Respiratory Impedance at Low Frequencies During Spontaneous Breathing Using the Forced Oscillation Technique
Hannes Maes, Clara-Mihaela Ionescu, Gerd Vandersteent

The forced oscillation technique (FOT) is a noninvasive method to measure the respiratory impedance Z, defined as the complex ratio of transrespiratory pressure P to the airflow at the airway opening Q as a function of frequency. FOT determines Z by superimposing small amplitude pressure oscillations on the normal breathing and measuring the resulting airflow. In this work a new approach for the analysis of the respiratory impedance Z at low frequencies (0.1-1 Hz) during spontaneous breathing is presented. When the respiratory impedance is measured in frequency ranges that overlap with the frequency of spontaneous breathing (0.1-1 Hz), the measured airflow will contain both the breathing of the patient and the response of the respiratory impedance to the pressure oscillations. A nonlinear estimator is developed which is able to separate the breathing signal from the respiratory response in order to obtain the respiratory impedance. The estimated results are used to obtain accurate estimates of airway and tissue components of a constant phase model.

Improving the $H$-infinity gain estimate of an Active Vibration Isolation System using Local Rational Models
Egon Geerardyn, Tom Oomen (TU/e), Johan Schoukens

Accurate uncertainty modeling is crucial in robust vibration controller design. A novel uncertainty modeling technique that enhances the estimated $H$-infinity norm of the model error based on the frequency response is developed in this paper. The major innovation is the use of the local rational method (LRM), a local parametric modeling method, to address the inter-grid error. Unlike classical frequency response function (FRF)-based methods that typically underestimate the $H$-infinity norm, the proposed technique allows to capture sharp resonance phenomena without the need for a user-intensive and time-consuming model selection step. The performance of the method is illustrated on a simulation example and on measurements of an industrial active vibration isolation system (AVIS). It is shown that in a short measurement time, a reliable estimate of the $H$-infinity gain can be attained. On the measurement data, a 7.5 dB improvement of the $H$-infinity norm is observed and validated.

Measurement of the best linear time-invariant approximation of linear time-periodic systems
Louarroudi, E., J. Lataire, and R. Pintelon

Time-periodic (TP) phenomena occurring, for instance, in wind turbines, helicopters, anisotropic shaftbearing systems, reciprocating engines, ... are often not addressed when classical frequency response function (FRF) measurements are performed. As the traditional FRF concept is based on the linear time-invariant (LTI) system theory, it is only approximately valid for systems with varying dynamics. Accordingly, the quantification of any deviation from this ideal LTI framework is more than welcome. The "measure of deviation" allows us to define the notion of the best LTI (BLTI) approximation, which yields the best – in mean square sense – LTI description of a linear time-periodic LTP system. By taking into consideration the TP effects, it is shown in this paper that the variability of the BLTI measurement can be reduced significantly compared with that of classical FRF estimators. The theory presented is supported by a numerical example.

Experimental driven demystification of system identification for nonlinear mechanical systems
M.Vaes, J. Schoukens, Y. Rolain, J. Pattyn

The goal here is to develop a low cost hardware-based demonstrator for system identification (SI) methods that can be used in a self-paced training kit by students as well as practicing engineers. The focus lies on hands-on training with a high return on effort. It starts from experiments that are performed on the demonstrator, a real system that can easily be used at home by the trainee without the need for external support or expensive equipment. The advantage for the SI community is that the steep learning curve, that often scares potential users of advanced SI methods, is flattened while the practical applicability is demonstrated altogether. The joint use of teaching material and hardware-based illustration provides enough knowledge, understanding and confidence to apply these methods on industrial scale systems. The first test case, which is presented here, is a mechanical setup. It consists of a nonlinear mass-spring-damper system built using commonly available components for a total cost of less than 50 Euro. When applying a signal with a low amplitude to the designed system, it almost perfectly behaves in a Linear Time Invariant (LTI) way. This is only true whenever the amplitude of the input signal is very small. Increasing the amplitude introduces weak and intuitive nonlinear distortions. Increasing the amplitude even further challenges the trainee's intuition even more. A sweep up and sweep down sine test shows that the system becomes bistable around the resonance peak which shifts in frequency with increasing amplitude. These phenomena are typical for a nonlinear vibrating system containing jumps. The main payback for the trainee is that the well-known Frequency Response Function (FRF) measurement of the mechanical system can also be used as an enabler for the nonlinear SI. The experiment shows the need for the quantification of nonlinear effects. Existing high return local linearization methods are introduced and applied directly to the system under test. The major advantage of these real experiments lies in the direct visual feedback provided to the user. A first presentation of the setup to test groups already involved in SI seems to indicate that the approach can strongly stimulate, motivate, attract and help potential users.

Consistent estimation of autonomous linear time-invariant systems from multiple experiments
Markovsky, I., and R. Pintelon
Annual report ELEC 2014


Operational modal analysis from impulse response data can alternatively be viewed as an identification of a stable autonomous linear time-invariant system. For example, earthquake response data of civil engineering structures and impulsive excitation of bridges leads to this problem. Identification from a single experiment, however, does not yield a consistent estimator in the output-error setting due to the exponential decay in the noise-free signal. Using data from multiple experiments, on the other hand, is not straightforward because of the need to match the initial conditions in the repeated experiments. Consequently, we consider the identification from arbitrary initial conditions and show that consistent estimation is possible in this case. The computational method proposed in the paper is based on analytic elimination of the initial conditions (nuisance parameter) and local optimization over the remaining (model) parameters. It is implemented in a ready to use software package, available from http://slra.github.io/software.html

5.6 ABSTRACTS (2014)

a309. Identification of Linear Time Varying Systems in the Time Domain using B-Splines

CSURCSIA Péter Zoltán, SCHOUKENS JOANNES, KOLLÁR István
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

This paper presents the first result of the nonparametric time domain identification for linear slowly time-variant systems. The proposed B-spline method uses a two dimensional impulse response function hLT[t(t)]. Unlike the linear time invariant systems where the impulse response function is unique, the time varying impulse response is not restricted to only one solution. Assume that the length of input and output is N, then the possible variations for the impulse response function are N2. Hence there is no unique impulse response function that relates the input to the output, because there are only N linear relations for O(N2) unknowns. The user can impose additional constrains to decrease this freedom, for instance smoothness. In the proposed case a generalized smoothing spline is used once over the system time t (direction
of the impulse responses, referring to the behavior) and once over the global time \( t \) (referring to the system memory). The excess degrees of freedom are removed using a generalized B-spline smoothing technique [1] [3].

**a310. Distortion Contribution Analysis by combining the MIMO BLA and noise analysis**

Adam Cooman and Gerd Vandersteen

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

To be able to cope with ever more stringent specifications in terms of linearity, designers of analog electronic circuits need tools to effectively reduce the distortion generated in their circuits. A first step in solving this problem is to find the disturbing source. Our goal is to develop a simulation-based method which shows the dominant sources of non-linear distortion in an electronic circuit. To be useful during the design, the analysis should be fast and should avoid the use of special simulation techniques and/or device models. The method combines the Best Linear Approximation BLA) with existing noise de-embedding techniques from the microwave measurement community [1]. The BLA allows to consider the distortion added by every stage as noise. Combining the BLA with a noise analysis allows to pinpoint the dominant source of non-linear distortion [2]. At high frequencies, the input impedance and reverse gain of amplifier stages play an important role. Taking these effects into account requires a port representation of the stages and the interconnection network. This leads to the distortion contribution analysis based on the MIMO BLA [3]. The different steps of the analysis are described below. This new analysis can be used hierarchically from the system level, down to the transistor level.

**a311. FRF estimation in the presence of missing output data**

Diana Ugrayumova, Rik Pintelon and Gerd Vandersteen

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Nonparametric Frequency Response Function (FRF) estimation is of high importance in engineering. Nonparametric models need fewer assumptions and provide quickly useful information about the considered dynamic system. The major challenge in the FRF estimation is the reduction of the leakage errors while keeping the variance of the estimators low. The leakage errors, also called the transient effect, originate from the difference between the initial and final conditions of the experiment. Windowing methods are used in spectral analysis to estimate the FRF from time domain measurements. Recently, a method, called Local Polynomial Method (LPM), was developed that suppressed better the leakage error by estimating nonparametrically the FRF and the leakage error [1].

**a312. Linking regularization and low-rank approximation for impulse response modelling**

Anna Marconato, Lennart Ljung, Yves Rolain, Johan Schoukens

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

In the last years, nonparametric linear dynamical systems modeling has regained attention in the system identification world. In particular, the application of regularization techniques that were already widely used in statistics and machine learning, has proven beneficial for the estimation of the impulse response of linear systems too. The low-rank approximation of the impulse response obtained by the truncated singular value decomposition (SVD) also leads to reduced complexity estimates. In this work, the link between regularization and SVD truncation for finite impulse response (FIR) model estimation is made explicit. The SVD truncation is reformulated as a regularization problem with a specific choice of the regularization matrix.

**a313. Modeling a broadband Doherty power amplifier using a parallel Wiener-Hammerstein model**

M. Schoukens, M. Özen, C. Fager, M. Thorsell, G. Vandersteen, Y. Rolain

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Microwave Doherty power amplifiers exhibit some nonlinear distortion behavior. This paper proposes to use a parallel Wiener-Hammerstein model to explain the in-band and spectral regrowth nonlinear effects that are present in the output of the system. The model is compared with some state of the art modeling techniques on measured data.

**a314. Use of Gaussian Processes for Frequency Response Function estimation**

John Lataire, Tianshi Chen

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

In system identification, the selection of the model complexity is a tedious task. It can be alleviated by the use of statistical learning tools, like Gaussian processes. The selection of the model complexity is, then, formulated as a gradient based optimisation. In this work Gaussian processes are used to estimate the frequency response function, via a frequency domain formulation. A complexity/variance trade-off is obtained via a Bayesian framework. The novel contribution w.r.t. closely related work is the frequency domain formulation, yielding specific advantages, including the selection of the frequency band of interest.

**a315. Initial estimates for Wiener-Hammerstein models via basis function expansions**

Koen Tiels and Johan Schoukens

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Block-oriented models are often used to model nonlinear systems. They consist of linear dynamic (L) and nonlinear static (N) sub-blocks. In this talk, a method to generate initial values for a Wiener-Hammerstein model (LN cascade) is proposed. The method starts from the best linear approximation (BLA) of the system, which provides an estimate of the product of the transfer functions of the two linear dynamic sub-blocks. Next, the poles of the BLA are assigned to both linear dynamic sub-blocks. The linear dynamics are then parameterized in terms of rational orthonormal basis functions, while the nonlinear sub-block is parameterized by a polynomial. This allows us to reformulate the model to the cascade of a parallel Wiener (with parallel LN structure) and a linear dynamic system, which is bilinear in its parameters. After a bilinear optimization, the parallel Wiener part is projected to a single-branch Wiener model. The approach is illustrated on a simulation example.

**a316. Estimation of respiratory impedance on breathing patients**

Hannes Maes & Gerd Vandersteen

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014
The respiratory impedance \( Z \) is a widely used quantity for the monitoring of lung diseases. The measurement technique to obtain the respiratory impedance is commonly known as the forced oscillation technique (FOT). A small amplitude pressure oscillation \( p \) (in the order of 0.1 kPa) is imposed on the patients breathing and the resulting airflow \( q \) generated by the patient is measured. The respiratory impedance \( Z \) is defined as the frequency dependent ratio between the imposed pressure and the airflow at the mouth of the patient. In this work the respiratory admittance \( G = 1/Z \) is considered. The main benefit of FOT is that it hardly requires any effort from the patient in contrast to, for example, spirometry. It has been shown that a lot of useful information is contained in the frequency range of spontaneous breathing 0.1 – 1 Hz [1].

Therefore, a setup is developed that is able to generate pressure oscillations that are in the presence of spontaneous breathing [2]. The next step consists in the analysis of the flow signal to obtain an estimate of the respiratory admittance. Therefore the response of the respiratory system \( q_{resp} \) needs to be obtained. This response is strongly impeded by the presence of the breathing signal \( d_{br} \). As illustrated in Fig. 1 the measured airflow consists of both the breathing signal \( d_{br} \) and the response of the respiratory system \( q_{resp} \). Both signals will generate power in the same frequency band (0.1 - 1 Hz), which demands for a good model of the breathing signal in order to obtain the response of the respiratory admittance.

### a317. The Local Rational Method Estimates the H-infinity gain using Less Data

**Egon Geerardyn, Tom Oomen, Johan Schoukens**

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

In this work we present the use of the Local Rational Method to estimate the H-infinity gain of an Active Vibration Isolation System. The proposed method works by estimating low-order local rational models over the frequency, interpolating them and retaining the largest amplitude of the transfer function of the model-error. On measurements, it has been shown that the LRM-interpolation yields a 7.5 dB improvement in the estimated H-infinity norm and that the estimate is in agreement with four times longer data record. This indicates that the LRM-interpolation is able to provide a reliable H-infinity gain estimate in a very short measurement time.

### a318. Identification of nonlinear dynamic systems: NL-LFR approach, the MIMO case with several nonlinearities

**Laurent Vanbeylen, Anne Van Mulders**

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Earlier work has revealed that the NL-LFR (nonlinear linear fractional representation) model is a candidate model with high potential to identify practical nonlinear dynamic systems [1]. Here, the full multivariable case is presented, simultaneously extending the number of model inputs and outputs (vector signals), as well as introducing the possibility to account for the presence of two or more static nonlinearities (SNLs).

### a319. Error analysis of discrete-time models without a direct term for Band-Limited measurements

**Johan Schoukens, Rishi Relan**

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Most real systems and processes are continuous in nature but most of the control strategies are implemented using a digital computer. Therefore a discrete-time representation of the continuous-time system under consideration is required in order to achieve a good performance in control as well as simulation. These discrete-time representation of the continuous time system can be developed under a zero-order hold (ZOH) or Band-limited assumption of the inter-sample behavior [7]. It is important to quantify the relative error of the approximate discrete-time models. In this paper, we analyze the additional error that is introduced by forcing the direct term of the discrete-time model equal to zero for the Band-limited measurements. Such models are more convenient when used to simulate nonlinear feedback systems. The presence of a delay removes the nonlinear algebraic loops so that simple recursive simulation becomes possible. In this work, we present for a special case, where both the generator and system are a first order continuous-time systems with same time constant i.e. \( \text{fgem} = \text{fsys} = \text{fb} \), an analysis of relative error of the discrete-time model with respect to the bandwidth and the sampling frequency under the Band-limited assumption. This analysis is important because the design of an identification experiment based on Band-Limited assumption is often more realistic, easier and appropriate to realize during identification of a complex nonlinear system as compared to the zero-order hold (ZOH) assumption.

### a320. On Decoupled Optimal Input Design for Nonlinear Systems with Infinite Memory

**Alexander De Cock, Johan Schoukens**

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

For linear dynamic systems the problem of optimal input design is well studied and well documented in the literature. Therefore, for nonlinear systems the field is still in development. Recently new progress has been made for nonlinear systems with limited memory. However extension of these methods to systems with large or infinite memory does not seem possible. In this work a new method is proposed in order to find a 0good O input for a system consisting of an IIR filter followed by a static nonlinearity. Instead of maximizing the determinant of Fisher information matrix of the whole system, which is hard because it is unclear on which properties of the input the matrix depends, an iterative method is proposed that alternately improves the determinants of the subsystems. During this optimization certain constraints are added in order to make the solution well defined. The influence of different constraints on the shape of the input is also investigated.

### a321. Frequency domain LPV state space identification for fast and slow periodic parameter variation

**Jan Goos, Rik Pintelon**

Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

We are studying the class of Linear Parameter-Varying (LPV) systems, where the system changes according to some kind of external signal (which we can measure). Current LPV controller synthesis tools (whils usually require a state space representation. Also, controllers are mostly implemented digitally, so we will directly try to identify a discrete state space model. There are some LPV identification techniques available, but they are usually restricted to either slowly or fast-varying scheduling sequences. Both cases fit in our frequency domain approach, and can be identified using the same
non-linear optimization routine. We can calculate the Jacobian very time-efficiently, because of the sparse structure in the frequency domain.

### a322. Macromodels for the Design of Microwave Filters
Matthias Caenepeel, Yves Rolain, Fabien Seyfert and Martine Olivi
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Microstrip filters increasingly exploit complex structures to optimize the performance-to-surface ratio. The design of these structures often boils down to massive electromagnetic (EM) optimization. A proposed alternative for this is a macromodel based design. A filter macromodel represents the dependence of the frequency response function (scattering or S-parameters) with respect to the design variables over a predefined range. For microstrip filters these variables, called meta-parameters, define the geometrical layout. Current state-of-the-art macromodels interpolate a set of well chosen “root” frequency response function (FRF) based on a pole-residue model. The “root” data are generated by a numerically expensive EM solver. A classical design uses the coupling matrix of the low-pass prototype filter rather than a pole-residue form. A macromodel in a design context, uses the low-pass coupling matrix representation to parameterize the “root” models instead. Intuitively the coupling parameters are expected to be more smooth dependent on the geometrical dimensions and hence well suited for interpolation purposes.

### a323. Nonlinear RF Measurement and modeling: going beyond the NVNA
Maral Zyari, Yves Rolain
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Characterizing the nonlinear behavior of systems operating at RF frequencies became popular during the last years [1]. Mainstream measurement setups use CW or two-tone excitations under variable impedance loading. They mainly provide power sweep capability at a fixed frequency. Extracted Figures Of Merit (FOM) allow a comparison of systems under standard operation but lack the expected modeling capability. One or two-tone based models increasingly loose reliability for practical signals that are often wide band and modulated. The reason for that lies in the static third order model that underpins all the FOMs. The alternative X-parameters or S-functions allow for more complicated nonlinearity, but mainly keep the (quasi-)static nature of the system. In this work, we propose a dynamic measurements and modeling framework based on modulated excitation signals. The aim is to recycle the simplicity of linear modeling to provide insight in nonlinear behavior.

### a324. Algebraic-Geometric Decoupling of Multivariate Polynomials
Philippe Dreesen en Johan Schoukens
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

Nonlinear system identification often makes use of multivariate polynomials to represent nonlinearities [2, 3]. For the sake of model interpretability and to limit the rapid increase of parameters it is desirable to find a parsimonious description of a given multivariate polynomial. From a given set of polynomials, a simplified representation may be obtained by considering a linear transformation of the unknowns, in order to retrieve a set of decoupled parallel univariate branches. We will investigate geometric properties of the problem and propose a decoupling strategy that works via the zero sets of the polynomial mappings, exploiting the linear relations between the coupled and the decoupled variables.

### a325. Adjusted least squares for algebraic hypersurface fitting
Konstantin Usevich, Ivan Markovsky
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

The problem of data modeling by nonlinear functions appears in many applied sciences. We consider the problem of finding an implicit polynomial relation that describes the given data in the best way. The problem is stated as an estimation problem in the errors-in-variables framework. The adjusted least squares estimator accounts for the bias present in the ordinary least squares estimator. Theoretical properties such as rotational/translational invariance are studied. An algorithm for computing the estimator for arbitrary support of the polynomial equation is presented. An application to subspace clustering is considered.

### a326. Experimental driven demystification of system identification for nonlinear mechanical systems
Mark Vaes, Johan Schoukens, Yves Rolain and Johan Pattyn
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

The goal here is to develop a low cost hardware based demonstrator for system identification (SI) methods that can be used in a self-paced training kit by students as well as practicing engineers. The focus lies on hands-on training with a high return on effort. It starts from experiments that are performed on the demonstrator, a real system that can easily be used at home by the trainee without the need for external support or expensive equipment.

### a327. Identification of a flexible block-oriented model
Anne Van Mulders and Laurent Vanbeylen
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014

In this work, the goal is to identify structured nonlinear systems, in particular block-oriented models. These models consist of linear dynamic and static nonlinear (S NL) blocks. The block-oriented model presented here, called NL-LFR (nonlinear Linear Fractional Representation), is very flexible and encompasses many other block-structures. The proposed identification approach is state-space based. First, a partly structured polynomial state-space model is identified, and next, the dynamics and nonlinearities are split algebraically, decomposing the multivariate polynomial coefficients.

### a328. Using the best linear approximation with varying excitation signals for nonlinear system characterization
FAKHRIZADEH ESFAHANI Alireza, Schoukens Johan, Vanbeylen Laurent
Benelux meeting, Heijen, The Netherlands, March 25-27, 2014
Since nonlinear (NL) identification is often very time consuming, it is highly desirable to carefully select a well suited model structure prior to the actual identification. In this study the focus is on the detection of the presence of NL components in the system. Therefore, the frequency response function (FRF) of the best linear approximation (BLA) is measured at different excitation signal settings. Two properties of the excitation are varied to analyze the nonlinear behavior:

1. Amplitude (RMS value) level
2. DC level (offset or set points)

Besides the measurement of the BLA, we make, at the same time, a non-parametric analysis of the nonlinear distortions. This can be done with either the robust method, or with the fast method. The goal of the study is to find out what is the best strategy to vary the excitation signal.

Fixed-size kernel models with SVD truncation schemes
Ricardo Castro, Siamak Mehrkanoon, Anna Marconato, Johan Schoukens, Johan A.K. Suykens
Benelux meeting, Heijden, The Netherlands, March 25-27, 2014

Criteria for assessing the generalization performance take the form Prediction Error = training error + complexity term. The complexity term represents a penalty growing with the number of free parameters in the model. We consider different versions of fixed-size kernel models related to fixed-size least squares support vector machines (FS-LSSVM) and consider the effective degrees of freedom (EDF) as the notion for model complexity.

Structured low-rank approximation by Factorization
M. Ishteva, K. Usevich and I. Markovsky
Lecture at International Conference on Numerical Methods for Scientific Computations, Bansko, Bulgaria, May 19–22, pp. 49-52

We first consider the problem of approximating an affinely structured matrix, for example a Hankel matrix, by a low-rank matrix with the same structure. This problem occurs in system identification, signal processing and computer algebra, among others. We consider a factorization approach and enforce the structure on the approximation by introducing a penalty term in the objective function. The proposed local optimization algorithm is able to solve the weighted structured low-rank approximation problem, as well as to deal with the cases of missing or fixed elements.

Structured matrix low-rank approximation and its application for solving tensor problems
M. Ishteva, K. Usevich, I. Markovsky
Invited lecture at the Structured Matrix Days, Université de Limoges, May 26-27

We first consider the problem of approximating an affinely structured matrix, for example a Hankel matrix, by a low-rank matrix with the same structure. This problem occurs in system identification, signal processing and computer algebra, among others. We impose the low-rank by modeling the approximation as a product of two factors with reduced dimension. The structure of the low-rank model is enforced by introducing a penalty term in the objective function. The proposed local optimization algorithm is able to solve the weighted structured low-rank approximation problem, as well as to deal with the cases of missing or fixed elements. In the second part of the talk we transform the symmetric tensor low multilinear rank approximation problem into a structured matrix low-rank approximation problem. In addition, by imposing linear constraints in the optimization problem, this approach is applicable to general (non-symmetric) tensors, as well as to affinely structured tensors, to find (locally) best low multilinear rank approximation with the same structure.

Bestimmung von vertikalen Grundwasser-Oberflächenwasseraustauschstraten mittels Temperaturzeitreihenanalyse am Beispiel des Slootbeek.
Schneidewind, U., Anibas, C., Vandersteen, G., Joris, I., Batelaan, O., Schmidt, C.

The complexity term represents a penalty growing with the number of free parameters in the model. We consider different versions of fixed-size kernel models related to fixed-size least squares support vector machines (FS-LSSVM) and consider the effective degrees of freedom (EDF) as the notion for model complexity.

Structured low-rank approximation with missing data
Mariya Ishteva, Konstantin Usevich and Ivan Markovsky
Presentation of poster at the householder Symposium XIX on Numerical Linear Algebra, Spa, Belgium, June 6-13, 2014
5.7 WORKSHOPS (2014)

w199. Macromodeling of narrow-band bandpass filters based on interpolation of coupling matrices
Matthias Caenepeel, Yves Rolain
2014 IEEE 18th Workshop on Signal and Power Integrity (SPI), Ghent, Belgium, 11-14 May 2014, pp. 1 - 4
Microwave filters increasingly exploit complex geometric structures to optimize the performance-to-surface ratio. This often leads to massive electromagnetic (EM) optimization based designs. Lately, macromodel-based designs are proposed as an intuition restoring alternative path. This comes at the cost of a rather numerically expensive model extraction cost. To reduce this extraction cost and to link the macromodel in a design context, the paper proposes to use a macromodel for the low-pass coupling matrix of the filters.

w200. A preliminary study on D-Optimal Input Design for Nonlinear Systems
Alexander De Cock, Johan Schoukens
Presentation of poster at the DYSCO Study Day Namur, May 16, 2014
Optimal input design is an important step of the identification process in order to reduce the model variance. In this work a D-optimal input design method for FIR-type nonlinear systems is presented. The optimization of the determinant of the Fisher matrix is expressed as a convex optimization problem. The optimization is performed using an equivalent dispersion-based criterion. This method is easy to implement and converges monotonically to the optimal solution. Without constraints, the optimal design cannot be realized as a time sequence. By imposing that the design should lie in the subspace described by a symmetric and non-overlapping basis, a realizable design is found. Next, a graph-based method is implemented in order to find a time sequence that realizes this optimal constrained design.

w201. Study of the effective number of parameters in nonlinear identification benchmarks
Anna Marconato, Maarten Schoukens, Yves Rolain and Johan Schoukens
Presentation of poster at the DYSCO Study Day Namur, May 16, 2014
This poster discusses the importance of the notion of effective number of parameters as a measure of model complexity. Exploiting this concept allows a fair comparison of models obtained from different model classes. Several illustrative examples of linear and nonlinear models are presented to provide more insight in the problem. A number of possibilities to reduce the model complexity are also discussed, including regularization techniques and an alternative approach based on rank reduced estimation. These ideas are then applied to two nonlinear real world problems: the Wiener-Hammerstein and the Silverbox benchmarks.

w202. The Local Rational Method for H-infinity Norm Estimation
Egon Geerardyn, Johan Schoukens
Presentation of poster at the DYSCO Study Day Namur, May 16, 2014
Accurate uncertainty modeling is of key importance in high performance robust control design. This poster shows a new uncertainty modeling procedure that enhances the accuracy of the H-infinity norm. A frequency response based approach is adopted. The key novelty is a method to address the intergrid error using local parametric modeling methods by means of the Local Rational Method (LRM). These local rational models enhance the estimates at the discrete frequency grid. Moreover, the presented methods are shown to enhance the intergrid error estimate. Compared to the local polynomial models, local rational models are able to handle lightly-damped resonances using far fewer data points and a far shorter measurement time. This is illustrated using experiments on an industrial active vibration isolation system.

w203. Nonparametric FRF estimation from data with partially missing output
Diana Ugaryumova, Rik Pintelon, Gerd Vandersteen
Presentation of poster at the DYSCO Study Day Namur, May 16, 2014
Nonparametric frequency response function (FRF) estimation is a quick and relatively easy way of getting information about a system from input-output measurements. Samples are sometimes missing due to imperfect measurement devices or communication links. If redoing the measurement is not possible, we need to find a way to accurately estimate the FRF while some measurement samples are missing. Here we extend the existing Local Polynomial Method (LPM, Pintelon et al) by putting the missing samples as additional (global) unknowns. LPM estimates a nonparametric frequency response of the system in the frequency-domain from time-domain input-output data, taking into account the difference between the initial and final conditions of the experiment (the transient effect). The only assumptions we make are that the input has a Drougou frequency spectrum and that the frequency response can be approximated locally by a polynomial. We show that the method can handle different missing patterns, random or one block, and that even with 50% of output missing we get very good results: an accurate estimate of the FRF, the output noise variance and the noiseless values of the missing samples with their uncertainty.
w204. Decoupling multivariate functions in block-oriented system identification: a linearization approach
Philippe Dreesen, Mariya Ishteva, Johan Schoukens
Block-oriented non-linear system identification uses static non-linear multivariate functions to describe the non-linear effects in a system. The identification procedure usually results in a multiple input multiple output static mapping where in general a coupling exists between the variables (e.g., in the case of multivariate polynomials cross-terms between the input variables show up). For the sake of model interpretability, as well as to avoid the curse of dimensionality, it is desirable to find an equivalent parsimonious description where the non-linear functions are decoupled in a set of parallel single input single output mappings acting between some unknown internal variables (that are related to the inputs and outputs by means of unknown linear transformation matrices). We solve this decoupling task by means of a linearization approach: the first-order behavior of the multivariate functions is obtained in a set of operation points (this procedure is similar to constructing the small-signal model of a nonlinear element). The decoupling task then easily leads to a simultaneous matrix diagonalization problem from which the unknown linear transformations follow, as well as the internal univariate mappings.

w205. Combining regularization and SVD truncation for impulse response modelling
Anna Marconato
In this work we consider the estimation of FIR models, in the situation where the system is excited with a colored noise input. For this problem, the application of regularization techniques has recently proven beneficial. Low-rank approximation methods based on the truncated SVD also lead to reduced complexity estimates. The link between these two approaches is shown by reformulating the SVD truncation as a regularization problem given a specific choice of the regularization matrix. Moreover, the two methods are combined, to include in the prior both the assumptions about the system and the information about the coloring of the input data. The results show the advantage of these techniques for impulse response estimation.

w206. Estimating the Best Linear Approximation in electronic circuits
Adam Cooman, Piet Bronders and Gerd Vandersteen
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
The Best Linear Approximation (BLA) is a useful tool for the design and analysis of non-linear electronic circuits. It allows to look at the performance of the non-linear circuit from the familiar linear world which gives an intuitive look into the circuit without having to simplify the class of excitation signals or using special models to describe the system. Looking at the complete behaviour of a circuit requires a port-based approach, where both voltages and currents are considered at each terminal of a circuit. The port-based approach leads to the familiar impedance (Z), admittance (Y) or scattering (S) parameters, which use a Multiple-Input Multiple-Output (MIMO) system to describe the full behaviour of the circuit. Introducing the BLA into this framework means that we need a fast and reliable way to determine the MIMO BLA of a sub-circuit in an electronic circuit. The identification of the MIMO BLA is a well-studied problem but, when we try to apply the default techniques to electronic circuits, extra questions arise: Determining the MIMO BLA requires two sources. Where to place the extra sources? Are voltage sources the best option, or should current sources be used? Can we tell something about the circuit behaviour outside of the main excitation band? How can we minimise the amount of simulation time? With simulation examples, we illustrate the issues that pop-up when trying to apply the theory blindly. Then we’ll show how the BLA of a sub-circuit is properly determined.

w207. Regularised system identification, formulated in the frequency domain
John Lataire
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
Recently, the interest in regularisation techniques for system identification has seen a major growth. Regularisation allows for the incorporation of prior knowledge about the system into the identification procedure, allowing for a well considered bias-variance trade-off. This poster aims at discussing the advantages of formulating these regularised estimators in the frequency domain. The discussed estimators include Least-Squares Support Vector Machines for the identification of time-varying systems and Gaussian Processes for Frequency Response Function estimation. Advantages include a higher robustness w.r.t. correlated errors when performing cross validation, and the possibility of choosing the frequency band of interest.

w208. Identification of structured models for nonlinear systems
Johan Schoukens
Plenary lecture at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
The control community makes use of mathematical models intensively to design high quality controllers. These mathematical models are often obtained from first principles, making use of detailed knowledge about the physical laws that describe systems. The major advantage of such an approach is that it provides detailed physical models that give much insight into the problems studied, however, at the cost of a long and difficult modeling process. At the other end of the possible modeling strategies we find the data-driven approach, where all information is retrieved from experimental data. These models are called black box models, and it is usually less expensive and less time-consuming to get them. System identification theory was developed to address the need for good methods to estimate mathematical models from noisy data. Nowadays mature and inexpensive tools are available to derive good models for linear dynamic systems. However, many systems are nonlinear so that more advanced tools are needed. Nonlinear models are significantly more complex than linear models. This does not only affect the interpretability of the estimated model, also the model structure selection problem becomes more difficult. In this presentation I like to illustrate these problems and discuss some
possibilities to address the new challenges. A number of nonlinear modeling strategies will be discussed, considering unstructured and highly structured models.

w209. **Exploring the Performance of the D-Optimal Input Design for a Linear Second Order System with respect to the Frequency Grid**

Alexander De Cock, Johan Schoukens

*Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014*

The goal of D-optimal input design is to find the input sequence for which the uncertainty volume in the parameter space is minimal. This corresponds to a maximization of the determinant of the Fisher information matrix if the estimator is efficient and unbiased. For linear systems, it has been shown that this optimization problem is convex with respect to the power spectrum of the input. In order to make the problem tractable, the frequency band of interest is discretized into a uniformly spaced frequency grid. However, it is often neglected that working on a discrete grid can lead to performance degradation compared to the optimal design computed on the continuous frequency band. Our goal is to study this performance degradation for second order systems. Once the behavior of the performance degradation has been characterized for a second order system, the result will be generalized to higher order systems. This can be done by representing the higher order systems as a combination of second order systems.

w210. **Decoupling multivariate functions: a linearization approach**

Philippe Dreesen, Mariya Ishteva, Johan Schoukens

*Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014*

Block-oriented non-linear system identification uses static non-linear multivariate functions to describe the non-linear effects in a system. For the non-linear blocks the identification procedure provides a multiple input multiple output static mapping where in general a coupling exists between the variables (e.g., in the case of multivariate polynomials cross-terms between the input variables show up). For the sake of model interpretability, as well as to avoid the curse of dimensionality, it is desirable to find an equivalent parsimonious description where the non-linear functions are decoupled in a set of parallel single input single output mappings acting between some unknown internal variables (that are related to the inputs and outputs by means of unknown linear transformation matrices). We solve this decoupling task by means of a linearization approach: the first-order behavior of the multivariate functions is obtained in a set of operating points (this procedure is similar to constructing the small-signal model of a nonlinear element). The decoupling task then immediately leads to a simultaneous matrix diagonalization problem from which the unknown linear transformations follow, as well as the internal univariate mappings.

w211. **Identification of a flexible block-oriented model**

Anne Van Mulders and Laurent Vanbeylen

*Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014*

Previous work on the identification of a class of structured nonlinear systems is extended. The considered system is block-oriented (consisting of linear dynamic and static nonlinear (SNL) blocks) and is called NL-LFR (nonlinear Linear Fractional Representation). It is very flexible and encompasses many other block-structures. The previous result was devoted to the case of an NL-LFR model with several Single-Input Single-Output (SISO) SNLs. This is here extended towards several Multiple-Input Single-Output (MISO) SNLs. After the identification of a partly structured polynomial state-space model, the dynamics and nonlinearities are split algebraically, decomposing the multivariate polynomial coefficients. This algebraic split of multivariate polynomials is obtained by means of a tensor decomposition.

w212. **Benefits of the linear fractional representation in nonlinear block-oriented modelling**

Laurent Vanbeylen and Anne Van Mulders

*Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014*

Nonlinear block-oriented models are quite popular due to their simplicity. However, appropriate structure detection tools to select the most appropriate type of nonlinear block-oriented model are lacking, which constitutes a vast open problem. By taking a step back, and viewing the nonlinear system as a linear fractional transformation of a static nonlinearity (NL-LFR), the structure detection issue can be circumvented. In an NL-LFR, the nonlinearity is placed in a quite general linear dynamic environment, which delivers a structure where the full power of the MIMO linear identification tools can be reused. Moreover, the model is adequate to naturally describe the behavior of systems where one nonlinearity is dominant. The discussion will cover the definition, general properties, generalizations of the NL-LFR model and a number of application examples.

w213. **Quantifying the error of the discrete-time models with forced delay for band-limited measurements**

Rishi Relan and Johan Schoukens

*Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014*

Most real systems and processes are continuous in nature but most of the control strategies are implemented using a digital computer. Therefore a discrete-time representation of the continuous-time system under consideration is required in order to achieve a good performance in control as well as simulation. The discrete-time representation of the continuous time system can be developed under a zero-order hold (ZOH) or band-limited assumption of the inter-sample behavior. In this work, we analyze the additional error that is introduced by forcing the direct term of the discrete-time model equal to zero for the band-limited measurements. Such models are more convenient to simulate nonlinear feedback systems. The presence of a delay removes the nonlinear algebraic loops so that simple recursive simulation becomes possible. Theoretical errors bounds for such kind of approximated models are provided in the case of band-limited signals. Furthermore the results are validated experimentally. This analysis is important because the design of an identification
experiment based on band-limited assumption is often more realistic, easier and appropriate to realize during identification of a complex nonlinear system as compared to the zero-order hold (ZOH) assumption.

**w214. Tensors and structured matrices of low rank**
Mariya Ištěva and Ivan Markovsky

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

We present a new connection between higher-order tensors and structured matrices, in the context of low-rank approximation. In particular, we show that the tensor low multilinear rank approximation problem can be reformulated as a structured matrix low-rank approximation, the latter being an extensively studied and well understood problem. For simplicity, we consider symmetric tensors. By imposing simple constraints on the problem, the proposed approach is applicable to general tensors, as well as to affinely structured tensors to find (locally) best low multilinear rank approximation with the same structure.

**w215. Initial estimates for Wiener-Hammerstein models via phase-coupled multisines**
Koen Tiels, Maarten Schoukens, Johan Schoukens

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

Block-oriented models are often used to model nonlinear systems. These models consist of linear dynamic (L) and nonlinear static (N) sub-blocks. We propose a simple initialization method for a Wiener-Hammerstein model (UNL cascade). The product of the transfer functions of the two linear blocks can be easily obtained via the best linear approximation (BLA) of the system for a Gaussian excitation. Splitting the global dynamics over the individual blocks turns out to be more difficult. We propose a well-designed multisine excitation and a modified BLA on a shifted frequency grid. The input dynamics are shown to shift with a frequency offset that can be chosen by the user, while the output dynamics do not move. This allows us to separate the two linear blocks via a simple initialization method, based on a linear system identification step. Experimental results obtained from the Wiener-Hammerstein benchmark system illustrate the good performance of the method.

**w216. Structured low-rank approximation with missing data**
Ivan Markovsky and Konstantin Usevich

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

Problems in system identification, machine learning, and computer algebra can be posed and solved as minimization of a cost function subject to a rank constraint on a structured matrix. The rank is related to the complexity of the model and the structure is related to properties of the model, e.g., LTI models lead to Hankel structured matrices. Missing data may occur in data modeling due to sensor failures. In compressive sensing, measurements are intentionally skipped due to redundancy of the data. Finally, missing data can be used to compute a signal, e.g., the control signal in a model-free tracking problem. We present an optimization method for structured low-rank approximation with missing data based on a kernel representation of the rank constraint. The bilinear structure of the problem is effectively exploited via the variable projections principle. The core computational step of the method is the solution of a singular least-norm problem.

**w217. Modelling a mechanical tuner**
Maral Zyari, Yves Rolain

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

In microwave measurements a tuner is used to vary the load of the nonlinear amplifier to assess its behavior. Therefore in a modulated measurement the impedance is to be controlled over a finite frequency band. In this work we are going to use a mechanical tuner with multiple (9) degrees of freedom to control the impedance over a desired finite bandwidth. To this end a surrogate model is built to predict and set the impedance of the tuner in a fast, accurate and reliable way. As models with multiple degrees of freedom are very hard to achieve, we lower the number of degrees of freedom by slicing the mechanical tuner in 4 chariots. Relying on the provided model we can speed up the measurement procedure.

**w218. Periodic Linear Parameter-Varying identification: state space and input-output models in the frequency domain**
Jan Goos, Rik Pintelon

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

The goal of this research is to identify an LPV model suited for control. We therefore opt for a state space form. In previous work, we proposed an LPV state space identification scheme, that was initialized with the Best Linear Time-Invariant (BLTI) approximation. We compare these previous results with an new initialization from an (identified) input-output model, that is realized exactly as a canonical state space form. This representation however, depends on (higher) order time derivatives of the coefficients of the differential equation. Therefore, in a second step, an optimization routine searches for an equivalent state space instance that has only a static dependency on p(t). Such a model would be very suited for LPV control.

**w219. Frequency response matrix estimation from partially missing data**
Diana Ugrayumova, Rik Pintelon, Gerd Vandersteen

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

The Frequency Response Matrix (FRM) gives a nonparametric description of a Multiple-Input-Multiple-Output (MIMO) dynamic system in the frequency domain. FRM estimation quickly provides information about the behavior of a system from input-output measurements without making too many assumptions. In model estimation, we often assume to have
access to the full measurement set of a system. Nevertheless, measurement devices, sensors and data communication links are prone to failures, which can result in partially missing measurement data. Using the conventional identification methods in this case could result in biased FRM estimates. Thus, our major goal is to find an accurate FRM estimate from partially missing output data. To achieve this we extend a recently developed method called Local Polynomial Method [Pintelon et al., MSSP, 2011] by adding the missing values as extra unknowns. We generalize the extended LPM in the presence of missing output data for single-input-single-output systems (presented at ERNSI 2013) to the multivariate case. The new method could also be used in case there are samples missing at the input and output of the system, provided that the reference signal is completely known.

w220. Modeling a broadband Doherty power amplifier using a parallel Wiener-Hammerstein model
Schoukens M., Özcn M., Fager C., Thorsell M., Vandersteen G., Rolain Y.
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
Microwave Doherty power amplifiers exhibit some nonlinear distortion behavior. This poster proposes to use a parallel Wiener-Hammerstein model to explain the in-band and spectral regrowth nonlinear effects that are present in the output of the system. The model is compared with some state-of-the-art modeling techniques on measured data. The proposed model obtains promising results, comparable to other modeling approaches that impose less structure, and that use more parameters in the model.

w221. Regularization in FIR estimation: only for short data records?
Anna Marconato and Johan Schoukens
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
In this work we consider the estimation of the impulse response of a linear dynamic system. When collecting a large amount of data represents an expensive and time-consuming procedure, an accurate estimate needs to be extracted based on a short input/output data record. Well-tuned regularization methods are getting popular to improve the impulse response estimates in this and other situations, by reducing the model variance. Although it is commonly believed that the beneficial impact of regularization is mainly evident for short data records, in this poster it will be shown that this is also the case when a large amount of data is available. This surprising result is illustrated by Monte Carlo simulations comparing regularization and standard least squares.

w222. The Local Rational Method for H-infinity Norm Estimation Reduces Measurement Time
Egon Geerardyn, Tom Oomen (TU/e), Johan Schoukens
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
In the design of robust controllers, the plant model uncertainty plays a crucial role. Based on frequency response function measurements its H-infinity norm is easily underestimated since it may contain sharp resonance peaks which are sampled using a limited frequency resolution. This can result in overly optimistic controllers that fail to attain the required performance and/or stability requirements. In this poster we estimate the H-infinity norm using the Local Rational Method (LRM). By combining low-order local rational models one obtains a more detailed view of a frequency response function and its H-infinity norm. Using this strategy, the H-infinity norm estimate is improved in a short measurement time. This is illustrated on an industrial active vibration isolation system where an increase can be observed and validated against a much larger data set.

w223. Analysis of breathing disturbances for the estimation of respiratory impedance
Hannes Maes and Gerd Vandersteen
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
Measurement of the respiratory impedance of a patient is a clinically practical method for the monitoring of lung pathologies. The respiratory impedance is defined as a complex ratio of pressure and flow signals measured at the mouth of the patient. During the measurement, the pressure signal is controlled to excite frequencies starting from the range of spontaneous breathing (0.1-1 Hz) up to 5 Hz. The resulting flow signal consists of a combination of a response to the excited frequency lines and spontaneous breathing disturbances. Since the spontaneous breathing disturbances have a higher amplitude in the low frequency range (0.1-1 Hz), separation techniques are needed to distinguish response to the excitation and breathing disturbances. The main difficulty during the separation stems from the variation of the breathing signals during the measurement. Both amplitude and fundamental frequency can show large and unpredictable changes during the measurement. Therefore, a combination of regularized least square estimators and random walk techniques is proposed in order to obtain estimates for the respiratory impedance.

w224. Macromodeling of narrow-band bandpass filters based on the interpolation of coupling matrices
Matthias Caenepeel, Yves Rolain, Fabien Seyfert (INRIA, France) and Martine Olivi (INRIA, France)
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014
Microwave filters increasingly exploit complex geometric structures to optimize the performance-to-surface ratio. This often leads to massive electromagnetic (EM) optimization based designs. Lately, macromodel-based designs are proposed as an intuition restoring alternative path. This comes at the cost of a rather numerically expensive model extraction cost. To reduce this extraction cost and to link the macromodel in a design context, we propose to build macromodel based on the low-pass coupling matrix representation of the filter.
w225. A preliminary look at the self-study kit for dissemination of nonlinear system identification
Mark Vaes, Johan Schoukens and Yves Rolain

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

Practitioners in industry often face nonlinear systems but nevertheless use linear Time Invariant (LTI) identification due to restricted dissemination of nonlinear identification knowledge. Being aware that most systems can behave nonlinearly, there is a need for a more widespread knowledge about the nonlinear system identification (SI) in general and the NL detection in particular. The goal of this work is to create a self-study kit to introduce this knowledge to the practitioner in a practical and self-contained way. The focus is put to obtaining useful, intuitive, and usable hands-on knowledge of nonlinear SI. To this end, every step is applied to a small practical but real test case system in order to keep the gap between theory and practice very small. A small mechanical test case system is already built to support the self-study kit. The self-study kit will support more than a linear learning process to allow users, with different background knowledge, learn nonlinear SI. It will be created in a cross-linked modular way. This allows a user without previous knowledge to learn the identification process step by step, while an experienced user will be able to cherry-pick the knowledge required without wasting too much time on searching information.

w226. A first attempt to optimal experiment design for system identification under regularized parameter estimation
Georgios Birpoutsoukis and Johan Schoukens

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

This work constitutes a first attempt to investigate the optimal input that must be applied to a dynamic system when regularization is used during the identification procedure. Regularization for parameter estimation has been widely used in function characterization and machine learning techniques. It has been recently shown that the regularized estimation can be very useful in the field of system identification. The key idea lies in manipulating the bias-variance trade-off of the estimated model parameters by introducing a penalty term in the cost function under minimization. Since the penalizing term in the cost function depends on the input-output measured data, it is important to investigate which input is going to deliver the optimal bias-variance trade-off measured through the Mean Square Error (MSE) of the estimated parameters. The fact that the regularization penalty can be considered as prior information about the unknown system incorporated in the cost function allows to exploit the properties of the input and the penalty introduced in the cost function. Since the penalty depends on the system input under optimization, the problem of optimal input design under regularized estimation boils down to optimizing both the input and the penalty introduced in the cost function.

w227. Retrieving structural nonlinear information using the best linear approximation
Alireza Fakhrizade Esfahani, Johan Schoukens and Laurent Vanbeylen

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

Since nonlinear (NL) identification is often very time consuming, it is highly desirable to carefully select a well suited model structure prior to the actual identification. In this study the focus is on the detection of the presence of NL feedback. Therefore, the frequency response function (FRF) of the best linear approximation (BLA) is measured at different excitation signal settings. Two properties of the excitation are varied to analyze the nonlinear behavior: 1. Amplitude (RMS value) level 2. DC level (offset or set point) The goal of the study is to find out what is the best strategy to vary the excitation signal, in order to obtain information about the structure of the system. Two case studies will be presented on different NL-feedback systems.

w228. Full nonparametric identification of the instantaneous dynamics of linear time-periodic systems
Ebrahim Louarroudi, Rik Pintelon and John Lataire

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

As (quasi) time-periodic (TP) systems are encountered in many engineering applications, ranging from reciprocating devices in the field of mechanics, through harmonic distortions in power distribution networks, to cardio-vascular monitoring in the bio-medical science, the extraction of experimental linear time-periodic (LTP) models meant for physical interpretation, analysis, prediction or control can be a useful step for the practicing engineer. Most of the identification methods available in the LTP literature are (non-)parametric-in-the-dynamics and parametric-in-the-time-variations. Because a full nonparametric model avoids a model order selection for the dynamics as well as for the time-variation part, it is more than welcome to have full nonparametric identification tools at hand. Estimation schemes, which are both nonparametric-in-the-dynamics as well as in-the-time-variations, for slowly varying dynamics are based on the short-time Fourier transform (STFT) principle. However, this can be a very restrictive assumption for applications with fast time-variations. To circumvent this problem, we show that when the excitation is a stationary random process the identification problem boils down to the estimation of the time-periodic cross-power spectral density (PSD) in the extended Wiener-Hopf relation: time-periodic cross-PSD = instantaneous dynamics ? input auto-PSD. This input-output relationship is always fulfilled irrespective of the speed and strength of the cyclic variations. As there is quite a lot of research done on how to estimate cyclo-/non-stationary auto-PSDs from noisy data, ideas can be used to estimate the time-periodic cross-PSD. For instance, by measuring a sufficient amount of system cycles an unbiased nonparametric estimate can be constructed for the time-periodic cross-PSD through synchronous averaging.

w229. Exploration of some nonlinear models structures for control
Julian Stoev and Johan Schoukens

Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

Nonlinear control is a very big and fast moving field with many important theoretical and practical challenges. Only a restricted number of nonlinear model classes can be used for designing a practical nonlinear control system and analytical conversion of one class of model into another class of model is often a task very far from trivial. On the other side nonlinear system identification has its own tools and challenges. It is important to make the nonlinear identification results relevant for the practical applications in nonlinear control. In this work we present from the identification viewpoint some polynomial nonlinear model structures, which are known to be relatively easy to control. We verify how some of these known structures can model our experimental system, which has a Wiener-Hammerstein structure. We evaluate the performance and complexity of the resulting models.

w230. Fixed-Size kernel models in System Identification under a reduced complexity perspective
Ricardo Castro, Siamak Mehrkanoon, Anna Marconato, Johan Schoukens, Johan A.K. Suykens
Presentation of poster at ERNSI 2014, European Research Network on System Identification, Oostende, Belgium, September 21-24, 2014

The goal of this work is to explore alternatives that allow the reduction of complexity of kernel models like Fixed Size Ordinary Least Squares (FS-OLS) and Fixed Size Ridge Regression (FS-RR). In general, black box approaches like these can achieve a good performance when undertaking system identification tasks, however, the complexity of the resulting models can be quite high. Under the conception that the Prediction Error is composed by a training error plus a complexity term, it is clear that a tradeoff between performance and complexity can be indeed a viable option. The focus of this work shifts from the traditional intention to maximize the performance to that of maximizing both: the performance and the complexity. This can result on a small loss of performance and a huge reduction of the complexity of the models used. Results found using Fixed Size Ordinary Least Squares and Fixed Size Ridge Regression on the Wiener-Hammerstein and Silverbox data set are presented.

w231. Transfer Function Estimation via Gaussian Processes Regression
John Lataire and Tianshi Chen
Presentation of poster at the DYSNSO study day, 12 November 2014, Ghent

Recently, the interest in regularization techniques for system identification has seen a major growth. Regularisation allows for the incorporation of prior knowledge about the system into the identification procedure, allowing for a well considered bias-variance trade-off. This poster demonstrates how this can be applied to the estimation of transfer functions. It is shown how the estimation of finite impulse responses via kernel based regression is transformed to the frequency. A spectral interpretation is provided for kernels which have been crafted especially for dynamic systems. Advantages are highlighted, like the possibility to select the frequency band of interest.

w232. A first attempt to optimal experiment design for system identification under regularized parameter estimation
Georgios Birkoutsoukis, Johan Schoukens
Presentation of poster at the DYSNSO study day, 12 November 2014, Ghent

This work constitutes a first attempt to investigate the optimal input that must be applied to a dynamic system when regularization is used during the identification procedure. Regularization for parameter estimation has been widely used in function characterization and machine learning techniques. It has been recently shown that the regularized estimation can be very useful in the field of system identification. The key idea lies in manipulating the bias-variance trade-off of the estimated model parameters by introducing a penalty term in the cost function under minimization. Since the penalizing term in the cost function depends on the input-output measured data it is important to investigate which input is going to deliver the optimal bias-variance trade-off measured through the Mean Square Error (MSE) of the estimated parameters. The fact that the regularization penalty can be considered as prior information about the unknown system incorporated in the cost function, can be exploited during the design of the optimal input. Since the penalty depends on the system input under optimization, the problem of optimal input design under regularized estimation boils down to optimizing both the input and the penalty introduced in the cost function.

w233. Modeling a broadband Doherty power amplifier using a parallel Wiener-Hammerstein model
Maarten Schoukens, M. Özen, C. Fager, M. Thorsell, G. Vandersteen, Y. Rolain
Presentation of poster at the DYSNSO study day, 12 November 2014, Ghent

Microwave Doherty power amplifiers exhibit some nonlinear distortion behavior. This poster proposes to use a parallel Wiener-Hammerstein model to explain the in-band and spectral regrowth nonlinear effects that are present in the output of the system. The model is compared with some state of the art modeling techniques on measured data.

w234. Retrieving structural nonlinear information using the best linear approximation
Alireza Fakhhrizade Esfahani, Johan Schoukens, Laurent Vanbeylen
Presentation of poster at the DYSNSO study day, 12 November 2014, Ghent

Since nonlinear (NL) identification is often very time consuming, it is highly desirable to carefully select a well suited model structure prior to the actual identification. In this study the focus is on the detection of the presence of NL feedback. Therefore, the frequency response function (FRF) of the best linear approximation (BLA) is measured at different excitation signal settings. Two properties of the excitation are varied to analyze the nonlinear behavior:

1. Amplitude (RMS value) level
2. DC level (offset or set points)

The goal of the study is to find out what is the best strategy to vary the excitation signal, in order to obtain information about the structure of the system. Two case studies will be presented on different NL-feedback systems.
5.8 SCIENTIFIC LECTURES (2014)

**sl35. What can System Identification Offer to Impedance Spectroscopy?**
Rik Pintelon
Seminar at the University of Warwick, School of Engineering on February 18, 2014
Via three motivating examples in impedance spectroscopy it is shown that real life systems often exhibit a (very) complex dynamic behaviour: they are nonlinear, time-variant, and - to some extend - non-repeatable. Hence, ideally one should identify a nonlinear time-variant model from a single experiment. This presentation reveals how system identification can contribute to this challenging task. First, the four basic choices for setting up a system identification experiment are discussed in detail. The following basic questions are handled: "What type of excitation signal should be used?", "What is the most appropriate experimental setup?", "Which model should be used?", "How to estimate the model parameters?". It will be shown that these basic choices are interrelated. Next, it is discussed how system identification can contribute to (non)parametric impedance spectroscopy. The following important questions are handled: "Does it make sense to approximate a nonlinear time-variant system by a linear time-invariant model?", "Which linear time-invariant model is the best?", "Can the deviation from the ideal linear time-invariant framework be detected and quantified?", "Is it possible to estimate (non)parametrically the time-variation?". Each issue is illustrated on real measurement examples. Finally, the presentation is summarised into one take home message.

**sl36. System Identification in a Real World**
Johan Schoukens
Invited speaker "une journée scientifique à L’Amphi Janet de Supélec, Le laboratoire des signaux et systèmes" on the occasion of the retirement of Éric Walter, 20 March, 2014
The control community makes use of mathematical models intensively to design high quality controllers. These mathematical models are often obtained from fist principles, making use of detailed knowledge about the physical laws that describe systems. e major advantage of such an approach is that it provides detailed physical models that give much insight into the problems studied, however, at the cost of a long and difficult modeling process. At the other end of the possible modeling strategies we find the data-driven approach, where all information is retrieved from experimental data. these models are called black box models, and it is usually less expensive and less time-consuming to get them. System identification theory was developed to address the need for good methods to estimate mathematical models from noisy data. Nowadays mature and inexpensive tools are available to derive good models for linear dynamic systems. However, many systems are nonlinear so that more advanced tools are needed. Building nonlinear models is much more involved, more expensive, and more time consuming than identifying a linear model. For that reason it is an important decision at the beginning of a design procedure, whether a linear or a nonlinear model should be identified. In the first part of this presentation it will be shown that it is possible to detect, qualify, and quantify the presence of nonlinear distortions. On the basis of this information it can be decided if an inexpensiv nonlinear model will be good enough for a successful design, or that a more elaborated nonlinear modeling effort should be made. In the second part, the impact of nonlinear distortions on linear system behavior will be discussed, so that the user gets a better understanding of the potential risks and problems when linear models are used in a nonlinear setting. Eventually, in the third part of the presentation a number of nonlinear modeling strategies will be discussed, considering unstructured and highly structured models.

**sl37. Nonlinear distortion analysis of circuits and systems**
Gerd Vandersteen and Adam Cooman
Tutorial 11 at the 2014 International Symposium on Circuits and Systems (ISCAS 2014), Melbourne, Australia, June 1, 2014
This tutorial aims to demystify the nonlinear distortion analysis of circuits and systems. Combining capability of analyzing large circuits through simulation-based methods and the analytical insight provided by symbolic methods enables the analysis of the nonlinear behavior of complex systems. The simulation-based methods make it possible to pinpoint the dominant nonlinearities, while the symbolic method can be used afterwards to get an analytical insight in the nonlinear behavior. This will be demonstrated using a large set of practical examples. The tutorial first introduces the necessary notions on Volterra theory, starting from classical linear system theory. The analytical expressions provided by Volterra result in a better understanding of the behavior of the system. The complexity of the resulting expressions, however, limits this technique to simple systems. Second, the tutorial introduces the Best-Linear-Approximation (BLA) paradigm, which represents the nonlinear system as a linear transfer function and additive nonlinear distortion components. It enables the separation of the various linear and nonlinear contributions and is able to pinpoint the dominant nonlinear distortions in a complex system and this in a hierarchical way. The main drawback of the simulation-based methods is, however, the reduced analytical insight. Finally, the power of both methods is illustrated on applications. Starting from a single-transistor circuit (a common source amplifier), the circuits complexity gradually increases over OPAMPs (different topologies), sigma-delta modulators and a receiver architecture. Both the symbolic method and the simulation-based methods are used side-by-side to gain insight in the nonlinear distortion properties of the system. All results are finally cross-checked and compared with publication results available in the literature.

**sl38. System identification in the behavioral setting: A low-rank approximation approach**
Ivan Markovsky, Konstantin Usevich and Mariya Ishteva

**sl39. Low-rank approximation problems in system identification**
Ivan Markovsky
Communications, Signal Processing and Control group, University of Southampton, UK, 21 August, 2014
Detection, Modeling and Identification of Nonlinearities in Engineering Structures
Gaetan Kerschen (Ulg), Johan Schoukens (VUB), Bart Peeters (LMS), Alex Carrella (LMS), Jean-Philippe Noel (Ulg), Wim Desmet (KULeuven)
2-Day Course at ISMA2014 International Conference on Noise and Vibration Engineering, Leuven (Belgium), Sept. 15-17, 2014
Operational modal analysis from impulse response data can alternatively be viewed as an identification of a stable autonomous linear time-invariant system. For example, earthquake response data of civil engineering structures and impulsive excitation of bridges leads to this problem. Identification from a single experiment, however, does not yield a consistent estimator in the output error setting due to the exponential decay of the noise-free signal. Using data from multiple experiments, on the other hand, is straightforward because of the need to match the initial conditions in the repeated experiments. Consequently, we consider the identification from arbitrary initial conditions and show that consistent estimation is possible in this case. The computational method proposed in the paper is based on analytic elimination of the initial conditions (nuisance parameter) and local optimization over the remaining (model) parameters. It is implemented in a ready to use software package, available from http://sitra.github.io/software.html

Recent Progress in Optimization for Dynamical Systems and Control
Ivan Markovsky
Department of Chemical Engineering, Katholieke Universiteit Leuven, 3 November, 2014

1. Decompositions of Higher-Oder Tensors: Concepts and Computation
Lieven De Lathauwer (KU Leuven), 20 February, 2014
For more than 20 years, decompositions of higher-order tensors have played a key role in research on independent component analysis and blind source separation. Nowadays tensors are intensively studied in many disciplines. They open up remarkable new possibilities in signal processing, array processing, data mining, machine learning, system modelling, scientific computing, statistics, wireless communication, audio and image processing, biomedical applications, bio-informatics, etc. On the other hand, tensor methods have firm roots in multilinear algebra, algebraic geometry, numerical mathematics and optimization. We give a brief introduction to the subject and discuss new trends and perspectives. We pay special attention to the current progress in numerical multilinear algebra. Results are illustrated using Tensorlab, our MATLAB toolbox for tensors and tensor computations of which version 2.0 has now been released.

2. System identification for operational modal analysis and structural health monitoring
Edwin Reynders (Dept. of Civil Engineering, KU Leuven), 6 March, 2014
This seminar focuses on two major applications of system identification in structural engineering: operational modal analysis and structural health monitoring. Operational modal analysis enables to determine modal characteristics - natural frequencies, damping ratios and mode shapes - of a structure in as-built, in-service conditions. It has a range of applications, such as design validation, model calibration, damage identification, and vibration control. Recent developments in system identification for operational modal analysis, such as uncertainty quantification and identification of combined deterministic-stochastic models, will be discussed in relation to these applications. Structural health monitoring relies on the repeated measurement of damage-sensitive features such as natural frequencies or quasi-static strains. A major problem is that regular changes in temperature and operational loading also influence those features. A potential solution is sought by identifying a nonlinear black-box model that describes the regular feature variations during a phase in which the structure is undamaged. Afterwards, the structure is monitored by comparing model predictions with observed features. A recently improved kernel principal component analysis approach will be presented in this context together with a validation study employing natural frequency data from a three-span prestressed concrete bridge, which was progressively damaged at the end of a one-year monitoring period.

3. Distribution Assumption Free Hypothesis Testing
Sándor Kolumbán (Budapest University of Technology and Economics), 20 March, 2014
Hypothesis testing methods that do not rely on exact distribution assumptions have been emerging lately in the system identification community. The method of sign-perturbed sums (SPS) is capable of characterizing confidence regions with exact confidence levels for linear regression and linear dynamical systems parameter estimation problems if the noise distribution is symmetric. This paper describes a general family of hypothesis testing methods that have an exact user chosen confidence level based on finite sample count and without relying on an assumed noise distribution. The only assumption made is that there is a group of transformations that leave the joint distribution of the noise invariant. It is shown that the SPS method belongs to this family and we provide another (meaningful) hypothesis test for the case where the symmetry assumption is replaced with exchangeability. In the case of linear regression problems it is shown that the confidence regions are connected, bounded and possibly non-convex sets in both cases. To highlight the importance of understanding the structure of confidence regions corresponding to such hypothesis tests it is shown that confidence sets for linear dynamical systems parameter estimates generated using the SPS method can have non-connected parts, which have far reaching consequences.

4. Model identification using $H_infty$-norm-based optimization algorithms: some new developments
Annual report ELEC 2014

Lecturer: Guillaume Mercère - University of Poitiers, France, 7 May, 2014

In this presentation, the challenging problem of estimating the unknown parameters of an identifiable structured linear time-invariant state-space representation is addressed by resorting to a specific $H_{\infty}$-norm-based optimization algorithm. Besides introducing an unusual system-based cost function which differs from the standard signal mathematical cost norm-based criterion, the $H_{\infty}$-norm is used herein as an efficient tool for adapting reliable and convergent non-smooth optimization algorithms. The system identification algorithm developed in this paper consists in (i) estimating a fully-parametrized linear time-invariant state-space form of the system from the available input-output data-sets by resorting to a standard estimation algorithm available in the literature, (ii) restructuring this reliable representation of the system dynamics via the optimization of the aforementioned $H_{\infty}$-norm-based criterion. The presentation of this new two-step identification technique as well as the simulation results will show that this $H_{\infty}$-norm-based approach can be seen as a good and moderate time consuming solution for the estimation of gray-box LTI state-space forms and, by extension, as an interesting alternative or initialization step for the standard output-error techniques. As a direct extension of this $H_{\infty}$-norm-based tool, the problems of the operating point selection as well as the identification of state-space LPV models from local data-sets are revisited and basic ideas of solution are introduced.

5. Progress and challenges in optimization methods for system identification and control

Ivan Markovsky (ELEC), 24 October, 2014

This talk reviews new results and challenges in system identification using
1. data from multiple experiments,
2. data with missing values, and
3. polynomial NARX model structure.

Multiple experiments is a practical issue in real-life identification problems. Moreover, multiple experiments allow us to relax the standard identifiability assumptions of stability and persistency of excitation. Thus, unstable and autonomous systems can also be estimated consistently. Fast methods for solving the corresponding optimization problem exist, so that dealing with the increased amount of data due to repeated experiments is as easy as dealing with the increased amount of data due to longer measurement time in a single experiment.

Missing data is another practical issue in real-life identification problems. It is also of interesting from a theoretical point of view. Computing the optimal control input for a unknown system (model-free control) is a missing data estimation problem, where the missing data is the control input. Contrary to the situation with multiple experiments, however, there are no fast and reliable methods for system identification with missing data. The key challenge in this area is, given a model, to find a recursive (Kalman filter-type) algorithm for missing data estimation.

Nonlinear system identification is a major research topic at ELEC. The presented results in this direction are experimental on the silver box benchmark. We use ell-1 norm regularization for structure selection and bias corrected least squares for subsequent parameter estimation. This part of the talk is primarily intended to stimulate links with ongoing activity in the department.

6. A simple explanation of kernel based regression

John Lataire (ELEC), 7 November, 2014

The last years, kernel based regression has been a buzz-word in the field of system identification. Kernel based regression comprises
- Gaussian process regression
- Least-squares support vector machines
- Regularised least squares

In this seminar, my goal is to explain kernel based regression via a toy example. The prerequisite knowledge is ordinary least squares. I will demystify the following concepts:
- how is it possible to work with an infinite basis?
- how can we formulate model complexity selection as a continuous optimisation problem?
- how does regularisation affect the bias-variance trade-off?

7. DC+noise+quantization: What do we know?

Paolo Carbone, University of Perugia, Italy, 3 December, 2014

Analog-to-digital conversion is a pervasive process in all modern systems and instruments. The conversion of an analog signal in the digital domain almost always results in a loss of information because of the limited resolution and accuracy of the quantizer embedded in the used analog-to-digital converter (ADC). This talk considers the case in which a constant value (DC) is converted using a noisy quantizer. Noise takes into account the effects due to device nonidealities in the realized ADC and the case in which dithering techniques are adopted. At first this topic will be explored to assess the information available at the quantizer output. Then the problem of estimating the input DC value will be analyzed, to show the performance of increasingly more complex estimators.

5.10 PATENTS

1. TDR Based Transfer Function Estimation of Local Loop

Tom Bostoen, Patrick Boets, Leo Van Biesen, Thierry Pollet and Mohamed Zekri
European Patent Office, Application No./Patent No. 01400832.0-1246

2. Method and Apparatus for Identification of an Access Network by Means of 1-Port Measurements
3. Method and Apparatus for Identification of an Access Network by Means of 1-Port Measurements

Tom Bostoen, Thierry Pollet, Patrick Boets, Mohamed Zekri and Leo Van Biesen

4. Method for Matching an Adaptive Hybrid to a Line

Tom Bostoen, Patrick Boets, Leo Van Biesen and Thierry Pollet
European Patent Office, Application No./Patent No. 03292891.3

5. Interpretation system for interpreting reflectometry information

T. Vermeiren, Tom Bostoen, Leo Van Biesen, Frank Louage, Patrick Boets

6. Interpretation system for interpreting reflectometry information

T. Vermeiren, Tom Bostoen, Leo Van Biesen, Frank Louage, Patrick Boets

7. Localisation of Customer Premises in a Local Loop Based on Reflectometry Measurements

Tom Bostoen, Thierry Pollet, Patrick Boets, Leo Van Biesen

8. Localisation of Customer Premises in a Local Loop Based on Reflectometry Measurements

Tom Bostoen, Thierry Pollet, Patrick Boets, Leo Van Biesen


Tom Bostoen, Thierry Pollet, Patrick Boets, Leo Van Biesen

10. Signal Pre Processing for Estimating attributes of transmission Line

Tom Bostoen, Thierry Pollet, Patrick Boets, Leo Van Biesen

11. A method for determining bit error rates

Vandersteen Gerd, Verbeeck Jozef, Rolain Yves, Schoukens Johan, Wambacq Piet, Donnay Stephane

12. A method for determining signals in mixed signal systems

Wambacq Piet, Vandersteen Gerd, Rolain Yves, Dobrovolny Petr
5.11 DOCTORAL DISSERTATIONS

PHD1. Etude de la Production et des Conditions de Propagation d'Ondes de Choc Créés par un Plasma de Décharge
Jean Renneboog
Doctoral Dissertation, Universit Libre de Bruxelles, 1967
Promoter: P. Baudoux (ULB)

PHD2. Bijdrage tot het Verwekken en Meten van Nauwkeurig Bepaalde Fazeverschuivingen
Alain Barel
Doctoral Dissertation, Vrije Universiteit Brussel, April 1976
Judging-committee: G. Maggetto (VUB), Verlinden (VUB), Hoffman (RUG), C. Eugène (UCL)
Promoter: J. Renneboog (VUB)

PHD3. Maximum Informatie Extractie door middel van een Optimaal Frequentie Domein Experiment
Guy Vilain
Doctoral Dissertation, Vrije Universiteit Brussel, March 1983
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), J. Cornelis (VUB), C. Eugène (UCL), Kerkhof, J. Vereecken (VUB), G. Vansteenkiste (VUB)
Promoter: J. Renneboog (VUB)

PHD4. Foutdetectie op Electrische Lijnen met behulp van een Digitale Behandeling van het Reflectogram
Leo Van Biesen
Doctoral Dissertation, Vrije Universiteit Brussel, April 1983
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), Baert (RUG), C. Eugène (UCL), Goossens, Kirschvinck, J. Tiberghien (VUB)
Promoter: J. Renneboog (VUB)

PHD5. Parameterestimatie in Lineaire en Niet-Lineaire Systemen met Behulp van Digitale Tijdsdomein Metingen
Johan Schoukens
Doctoral Dissertation, Vrije Universiteit Brussel, February 1985
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), P. Eykhoff (TU Eindhoven), C. Eugène (UCL), Hoffman (RUG), Spriet (RUG), O. Steenhaut (VUB), G. Vansteenkiste (VUB)
Promoter: J. Renneboog (VUB)

PHD6. Active Microstrip Antennas
Russell Dearnly
Doctoral Dissertation, Vrije Universiteit Brussel, June 1987
Judging-committee: G. Maggetto (VUB), L.P. Ligthart (TU Delft), O. Steenhaut (VUB), G. Szymanski (Tech. University of Poznan), J. Tiberghien (VUB), A. Van De Capelle (KUL)
Promoters: J. Renneboog (VUB), A. Barel (VUB)

PHD7. Analysis and Application of a Maximum Likelihood Estimator for linear Systems
Rik Pintelon
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), P. Eykhoff (TU Eindhoven), A. van den Bos (TU Delft), J. Vandewalle (KUL)
Promoters: J. Renneboog (VUB), J. Schoukens (VUB)

PHD8. Time Division Multiplexing in Optical Fiber Networks
Danny Sevenhans
Doctoral Dissertation, Vrije Universiteit Brussel, June 1988
Judging-committee: G. Maggetto (VUB), P. Kool (VUB), E. Stijns (VUB), R. Blondel (Universit de Mons), P. Bulteel (Atea), C. Eugène (UCL), Baert (RUG)
Promoters: J. Renneboog (VUB), A. Barel (VUB)

PHD9. Design of Optimal Input Signals with Minimal Crest Factor
Edwin Van der Ouderaa
Judging-committee: G. Maggetto (VUB), F. Delbaen (VUB), P. Eykhoff (TU Eindhoven), R. Pintelon (VUB), J. Renneboog (VUB), A. van den Bos (TU Delft), J. Vandewalle (KUL)
Promoter: J. Schoukens (VUB)
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PhD10. Channel Multiple Access Protocols for a Hydrological Multihop Packet Radio Network
Thomas J. Odhiambo Afullo
Doctoral Dissertation, Vrije Universiteit Brussel, June 1989
Judging-committee: G. Maggetto (VUB), L. Van Biesen (VUB), J. Tiberghien (VUB), P. Van Binst (VUB), A. Van Der Beken (VUB)
Promoter: A. Barel (VUB)

PhD11. Steady-State Analysis of Strongly Nonlinear Circuits
Eli Van Den Eijnde
Promoter: J. Schoukens (VUB)

PhD12. Knowledge-Based Spectral Estimation
James Ambani Kulubi
Judging-committee: G. Maggetto (VUB), R. Pintelon (VUB), A. Barel (VUB), W. Verhelst (VUB), O. Steenhaut (VUB), Hoffman (RUG)
Promoter: L. Van Biesen (VUB)

PhD13. Radar Cross Section Reduction using Multiple-Layer Strip Gratings
Gert Van Der Plas
Judging-committee: G. Maggetto (VUB), R. Van Loon (VUB), A. Van de Capelle (KUL), D. De Zutter (RUG), P. Delogne (UCL)
Promoters: A. Barel (VUB), E. Schweicher (KMS)

PhD14. Automated Diagnosis for Arbitrary Digital Circuits
Patrick Bakx
Judging-committee: G. Maggetto (VUB), M. Goossens (VUB), A. Barel (VUB), M. Verlinden (VUB), V. Jonckers (VUB), P. Vandeloo (UIA)
Promoter: L. Van Biesen (VUB)

PhD15. Measuring Nonlinear Systems - A Black Box Approach for Instrument Implementation
Marc Vanden Bossche
Judging-committee: G. Maggetto (VUB), R. Pollard (T.U. Leeds), P. Eykhoff (TU Eindhoven), D. De Zutter (RUG), Rik Pintelon (VUB), D. Ritting (Hewlett Packard - USA)
Promoters: A. Barel (VUB), J. Schoukens (VUB)

PhD16. Identification of Multi-Input Multi-Output Systems using Frequency-Domain Models
Patrick Guillaume
Doctoral dissertation, Vrije Universiteit Brussel, June, 1992
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), M. Van Overmeire (VUB), P. Eykhoff (TU Eindhoven), M. Gevers (UCL), J. Vandewalle (KUL)
Promoters: J. Schoukens (VUB), R. Pintelon (VUB)

Hugo Van hamme
Doctoral dissertation, Vrije Universiteit Brussel, June, 1992
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), F. Delbaen (VUB), M. Vanden Bossche (Hewlett Packard Belgium), A. van den Bos (TU Delft), B. De Moor (KUL), L. Ljung (University of Linköping)
Promoters: R. Pintelon (VUB), J. Schoukens (VUB)

PhD18. Identification of Linear Systems from Amplitude Information only
Yves Rolain
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), F. Delbaen (VUB), P. Eykhoff (TU Eindhoven), A. van den Bos (TU Delft), K. Godfrey (Univ. of Warwick, UK), J. Vandewalle (KUL)
Promoters: J. Schoukens (VUB), R. Pintelon (VUB)
PhD19. The Use of the Method of Moments in Designing NMR Antennas
Guido Annaert
Doctoral dissertation, Vrije Universiteit Brussel, December, 1993
Judging-committee: G. Maggetto (VUB), R. Van Loon (VUB), R. Luypaert (VUB-AZ), R. Turner, C. De Wagter (RUG), P. Van Hecke (AGFA-GEVAERT NV.), M. Lumori (VECO)
Promoters: A. Barel (VUB), M. Osteaux (VUB-AZ)

Luc Peirlinckx
Doctoral dissertation, Vrije Universiteit Brussel, June 1994
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), L. Bjørnø (TU Denmark), P. De Wilde (VUB), H. Leroy (KULAK), J. Van Campenhout (UG), J.P. Sessarego (CNRS-LMA, France)
Promoters: L. Van Biesen (VUB), R. Pintelon (VUB)

PhD21. Radar Cross Section Calculations of Three-Dimensional Objects, Modelled by CAD
Isabelle De Leenheer
Judging-committee: G. Maggetto (VUB), V. Stein, D. De Zutter (UG), A. Van De Capelle (KUL), R. Van Loon (VUB)
Promoters: A. Barel (VUB), E. Schweicher (KMS)

PhD22. Design and Realization of Low Crest Factor Broadband Microwave Excitation Signals
Tom Van den Broeck
Doctoral Dissertation, Vrije Universiteit Brussel, September 1995
Judging-committee: G. Maggetto (VUB), J. Tiberghien (VUB), L. Martens (UG), R. Pollard (University of Leeds), M. Vanden Bossche (Hewlett Packard Belgium)
Promoters: A. Barel (VUB), J. Schoukens (VUB)

PhD23. Accurate Experimental Modelling of Bounded Wave Propagation in Viscoelastic Materials
Dayu Zhou
Doctoral Dissertation, Vrije Universiteit Brussel, October 1995
Judging-committee: G. Maggetto (VUB), P. Guillaume (VUB), L. Bjarne (TU Denmark), H. Leroy (KULAK), M. Lumori (VECO), J.P. Sessarego (CNRS-LMA, France), I. Veretennicoff (VUB)
Promoters: L. Van Biesen (VUB), L. Peirlinckx (VUB)

PhD24. Calibration of a Measurement System for High Frequency Nonlinear Devices
Jan Verspecht
Doctoral Dissertation, Vrije Universiteit Brussel, November 1995
Judging-committee: G. Maggetto (VUB), J. Schoukens (VUB), A. Cardon (VUB), M. Vanden Bossche (Hewlett Packard, Belgium), L. Martens (RUG), B. Nauwelaers (KUL), U. Lott, A. Roddie, R. Pintelon (VUB), I. Veretennicoff (VUB)
Promoter: A. Barel (VUB)

PhD25. Performance with dielectric resonators at microwave frequencies for studying the pairing state in high-Tc superconductors
Andrei Mourachkine
Judging-committee: W. Van Rensbergen (VUB), G. Van Tendeloo (VUB), J. Drowart (VUB), N. Klein (IFF, Julich), V. Gasumyants (St. Petersburg)
Promoters: A. Barel (VUB), S. Tavernier (VUB), R. Deltour (ULB)

Gerd Vandersteen
Doctoral dissertation, Vrije Universiteit Brussel, April 1997
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), M. Gevers (UCL), L. Ljung (University of Linköping), A. van den Bos (TU Delft), J. Vandewalle (KUL)
Promoters: R. Pintelon (VUB), J. Schoukens (VUB)

PhD27. Frequency Domain Identification of Transmission Lines from Time Domain Measurements
Patrick Boets
Judging-committee: G. Maggetto (VUB), A. Cardon (VUB), A. Barel (VUB), M. Goossens (VUB), R. Pintelon (VUB), D. Baert (RUG), C. Eugène (UCL), J. Capon (Belgacom), J. Verspecht (Hewlett Packard, Belgium)
Promoter: L. Van Biesen (VUB)
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PhD28. **Nonparametric Identification of Nonlinear Mechanical Systems**
Stefaan Duym
Judging-committee: G. Maggetto (VUB), R. Pintelon (VUB), A. Barel (VUB), J. Vandewalle (KUL), J. Swevers (KUL), K. Worden (Univ. of Sheffield)
Promoters: J. Schoukens (VUB), M. Van Overmeire (VUB)

PhD29. **Design of Digital Chebyshev Filters in the Complex Domain**
Rudi Vuerinckx
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), M. Goossens (VUB), E. Dierickx (VUB), H. Spoelder (Vrije Universiteit Amsterdam), E. Petriu (SITE-Ottawa)
Promoters: Y. Rolain (VUB), J. Schoukens (VUB)

PhD30. **Caching in Dataflow-Based Instrumentation & Measurement Environments**
Eli Steenput
Doctoral dissertation, Vrije Universiteit Brussel, October 1999
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), M. Goossens (VUB), E. Dierickx (VUB), H. Spoelder (Vrije Universiteit Amsterdam), E. Petriu (SITE-Ottawa)
Promoters: Y. Rolain (VUB), J. Schoukens (VUB)

PhD31. **Standstill Frequency Response Measurement and Identification Methods for Synchronous Machines**
Jef Verbeeck
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), A. Barel (VUB), J. Deuse (Tractebel), I. Kamwa (Institut de Recherche d’Hydro-Québec), J.C. Maun (ULB), J. Schoukens (VUB)
Promoters: R. Pintelon (VUB), Ph. Lataire (VUB)

PhD32. **Nonlinear Identification with Neural Networks and Fuzzy Logic**
Jürgen Van Gorp
Doctoral dissertation, Vrije Universiteit Brussel, August 2000
Judging-committee: G. Maggetto (VUB), A. Barel (VUB), G. Horváth (Budapest University of Technology and Economics), P. Kool (VUB), Y. Rolain (VUB), J. Sjöberg (Chalmers University of Technology, Göteborg), J. Suykens (KUL)
Promoters: J. Schoukens (VUB), R. Pintelon (VUB)

PhD33. **Patient and staff dosimetry in diagnostic radiology**
Jessica Pages Pulido
Doctoral dissertation, Vrije Universiteit Brussel, September 2000
Judging-committee: A. Hermanne (AZ-VUB), J. Vereecken (VUB), P. Van den Winkel (VUB-cyclotron), M. Osteaux (AZ-VUB), H. Thierens (Universiteit Gent), M.A.O. Thijsse (St. Radboud Ziekenhuis Nijmegen), H. Mol (AZ-VUB), M. Sonck (VUB-cyclotron)
Promoters: R. Van Loon (VUB)

PhD34. **Experimental Study of the Wave Propagation Through Sediments and the Characterization of its Acoustical Properties by Means of High-Frequency Acoustics**
Steve Vandenplas
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), A. Barel (VUB), L. Bjørnø (Technical University of Denmark), J.P. Sessarego (CNRS-Marseille), O. Leroy (KULAK), L. Peirlinckx (Phonetics Topographies)
Promoter: L. Van Biesen (VUB)

PhD35. **High Spatial Resolution Experimental Modal Analysis**
Steve Vanlanduit
Judging-committee: G. Maggetto (VUB), R. Arruda (Univ. Est. de Campinas, Brazil), A. Barel (VUB), R. Pintelon (VUB), J. Swevers (PMA - KULeuven), M. Van Overmeire (VUB), H. Van der Auweraer (LMS International)
Promoters: J. Schoukens (VUB), P. Guillaume (VUB)

PhD36. **Development of New Measuring and Modelling Techniques for RFICs and their Nonlinear Behaviour**
Wendy Van Moer
Doctoral Dissertation, Vrije Universiteit Brussel, June 2001
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), R. Pollard (Univ. of Leeds, UK), D. Van Hoenacker (Univ. Catholique de Louvain), J. Schoukens (VUB)
Promoters: Yves Rolain (VUB), Alain Barel (VUB)
Annual report ELEC 2014

PhD37. Spectral and Kinetic Analysis of Radiation Induced Optical Attenuation in Silica: Towards Intrinsic Fibre Optic Dosimetry?
Borgermans Paul
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), J. Schoukens (VUB), I. Veretennicoff (VUB), B. Neerdael (SCK-CEN), M. Decton (SCK-CEN), David Griscom (Naval Research Laboratory, USA)
Promoter: Alain Barel (VUB)

PhD38. Multi-Carrier Modulation with Reduced Peak to Average Power Ratio
Zekri Mohamed
Doctoral Dissertation, Vrije Universiteit Brussel, February 2002
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), A. Barel (VUB), J. Tiberghien (VUB), P. Boets (VUB), G. Vanhoutte (Belgacom), S. Ropescu (Polytechnic Univ. of Bucharest)
Promoter: L. Van Biesen

PhD39. Parametric modeling and estimation of ultrasonic bounded beam propagation in viscoelastic media
Bey Temsamani Abdellatif
Doctoral Dissertation, Vrije Universiteit Brussel, February 2002
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), A. Barel (VUB), D. Van Hemelrijck (VUB), L. Peirlinckx (Phonic-Topographies, Ieper), O. Leroy (KULAK), Leif Bjørnø (Technical University of Denmark, Lyngby (DK)), Jean-Pierre Sessarego (Laboratoire d'Acoustique et de Mecanique, CNRS, Marseille (F))
Promoter: L. Van Biesen

PhD40. Measurement and modelling of the noise behaviour of high-frequency nonlinear active systems
Geens Alain
Doctoral Dissertation, Vrije Universiteit Brussel, May 2002
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), R. Pintelon (VUB), R. Pollard (University of Leeds, UK), D. Van Hoenacker (UCL), J.C. Pedro (Universidade de Aveiro, Portugal), A. Barel (VUB)
Promoter: Y. Rolain

PhD41. Model Based Calibration of D/A Converters
Vargha Balázs
Doctoral Dissertation, Vrije Universiteit Brussel, June 2002
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), A. Barel (VUB), B. Bell (NIST, USA), I. Kollar (TUB, Hungary), Y. Rolain (VUB), G. Vandersteen (VUB-IMEC)
Promoters: Johan Schoukens, István Zoltan (TUB)

PhD42. Frequency Response Function Measurements in the Presence of Non-Linear Distortions
Kenneth Vanhoenacker
Doctoral Dissertation, Vrije Universiteit Brussel, June 2003
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), A. Barel (VUB), P. Guillaume (VUB), H. Sol (VUB), J. Swevers (KUL), H. Van der Auweraer (LMS International)
Promoter: Johan Schoukens

PhD43. Identification of Nonlinear Systems using Interpolated Volterra Models
József G. Németh
Doctoral Dissertation, Vrije Universiteit Brussel, June 2003
Judging-committee: A. Barel (VUB), T. Dobrowiecki (Budapest University of Technology and Economics), M.P. Kennedy (University College Cork), R. Pintelon (VUB)
Promoters: Johan Schoukens, István Kollár (TUB)

PhD44. Identification of block-oriented nonlinear models
Philippe Crama
Doctoral Dissertation, Vrije Universiteit Brussel, June 2004
Judging-committee: G. Maggetto (VUB), J. Vereecken (VUB), P. Guillaume (VUB), L. Ljung (Linköping Universitet, Sweden), M. Verhaegen (TUD, The Netherlands), J. Vandewalle (KUL), A. Barel (VUB), R. Pintelon(VUB)
Promoters: Johan Schoukens, Y. Rolain

PhD45. Identification of the Time Base in Environmental Archives
Fjo De Ridder
Doctoral Dissertation, Vrije Universiteit Brussel, December 2004
Judging-committee: W. Baeyens (VUB), A. Barel (VUB), A. Berger (UCL), Ph. Lataire (VUB), G. Munhoven (Universiteit de Liège), D. Paillard (Centre d’Etudes de Saclay, Orme des Merisiers, France), J. Schoukens (VUB), J. Vandewalle (KUL), J. Vereecken (VUB)
Promoters: R. Pintelon, Frank Dehairs
**PhD46.** Optimisatie van patiënt dosissen, gekoppeld aan beeldkwaliteit, in de vasculaire radiologie  
Lara Struelens  
Doctoral Dissertation, Vrije Universiteit Brussel, January 2005  
Judging-committee:  
Promotor: R. Van Loon, co-promotors: H. Bosmans (KUL), F. Vanhavere (SCK-CEN)

**PhD47.** Modelling, Designing and Developing a Multidisciplinary Geodatabase GIS with the Implementation of RDBMS in conjuction with CAD and different GIS applications for the development of Coastal/Marine Environment  
Tesfazghi Ghebre Egziabeher  
Doctoral Dissertation, Vrije Universiteit Brussel, September 2005  
Judging-committee: E. Vandijck (VUB), F. Canters (VUB), A. Barel (VUB), S. Wartel (Royal Belgian Institute of Natural Sciences), L. Peirlinckx (Phoneics Topographics, Belgium)  
Promoters: L. Van Biesen and Marc Van Mole (Geography dept., fac. of Sciences)

**PhD48.** Modeling of Substrate Noise Impact on CMOS VCOS on a Lightly-Doped Substrate  
Charlotte Soens  
Promoters: M. Kuijk, Y. Rolain, P. Wambacq,  

**PhD49.** Evaluation of deep-sub-quarter micron CMOS technology: low noise amplifiers, oscillators and ESD reliability  
Dimitri Linten  
Promoters: Y. Rolain, P. Wambacq and M. Kuijk  
Judging-committee: G. Maggetto, J. Vereecken, A. Barel, M.I. Natarajan (Mentor IMEC), I. Smedes (Philips Semiconductors), M. Tiebout (Infineon)

**PhD50.** Verification and Correction of Test Signals with a Spectrum Analyzer  
Daan Rabijns  
Doctoral Dissertation, Vrije Universiteit Brussel, March 2006  
Promoters: G. Vandersteen, J. Schoukens  
Judging-committee: P. Lataire, J. Vereecken, I. Kollar (Budapest Univ. of Techn. & Economics), D. DeGroot (CCNi Measurement Service), P. Guillaume, W. Van Moer

**PhD51.** Impact and Mitigation of Analog Impairments in Multiple Antenna Wireless Communications  
Jian Liu  
Promoters: A. Barel, J. Stiens, G. Vandersteen  
Judging-committee: P. Lataire, J. Vereecken, L. Van der Perre (IMEC), V. Öwall (Lund University, Sweden), W. Van Moer

**PhD52.** Development and evaluation of a numerical method for the identification of a physical system described by a partial differential equation: a case study  
Kathleen De Belder  
Promoters: R. Pintelon, J. Schoukens  
Judging-committee: Ph. Lataire, J. Vereecken, J. Swevers (KUL), P. Guillaume, H. Van der Auweraer (LMS International), H. Sol, P. Roose (Cytec)

**PhD53.** Contributions to Large-Signal Network Analysis  
Frans Verbeyst  
Promoter: Y. Rolain  
Judging-committee: J. De Ruyck, Jean Vereecken, Alain Barel, Don DeGroot (CCNi Measurement Services, Andrews University, Michigan, USA), Rik Pintelon, Roger Pollard (University of Leeds, UK), Johan Schoukens, Steve Vnlanduit

**PhD54.** Contribution to severe weather and multimodel ensemble forecasting in Belgium  
David Dehenaew  
Doctoral Dissertation, Vrije Universiteit Brussel, November 2006  
Promoters: A. Barel, H. Decleir  
PHD55. **A system identification view on two aquatic topics: phytoplankton dynamics and water mass mixing**

Anouk de Brauwere


Promoters: Willy Baeyens, Johan Schoukens

Judging-committee: Robert Fiere, Frank Dehairs, Rik Pintelon, An Smeers-Verbeke, Joos Vandewalle (KUL), Eric Deleersnijder (UCL), Karline Soetaert (NIOO-KNAW), Johannes Karstensen (University of Kiel)

PHD56. **Ultra-Wideband transceiver for low-power low data rate applications**

Julien Ryckaert


Promoters: Yves Rolain, Piet Wambacq (IMEC)

Judging-committee: Annick Hubin, Rik Pintelon, Gerd Vandersteen, J. Rabaey (University of Berkeley, USA), M. Tiebout (Infineon Germany), Christof Debaes, C. Desset (IMEC)

PHD57. **Measuring, modeling and realization of high-frequency amplifiers**

Ludwig De Locht


Promoters: Yves Rolain, Gerd Vandersteen

Judging-committee: Annick Hubin, Rik Pintelon, Wendy Van Moer, Danielle VAnhovenacker (UCL), Andrea Ferrero (Politecnico di Torino), Christof Debaes (VUB), Marc Vanden Bossche (NMDG Engineering)

PHD58. **Body Area Communications: Channel characterization and ultra-wideband system-level approach for low power**

Andrew Fort


Promoters: Leo Van Biesen, Piet Wambacq (IMEC)

Judging-committee: Annick Hubin, R. Pintelon, G. Vandersteen, Y. Hao (Univ. of London), C. Desset (IMEC)

PHD59. **Algorithms for identifying guaranteed stable and passive models from noisy data**

Tom D’Haene


Promoter: Rik Pintelon

Judging-committee: Gert Desmet, Jean Vereecken, Patrick Guillaume, Paul Van Dooren (UCL), Tom Dhaene (UGent), Martine Olivi (INRIA), Gerd Vandersteen

PHD60. **Identification of Nonlinear Systems Using Polynomial Nonlinear State Space Models**

Johan Paduart


Promoters: Johan Schoukens, Rik Pintelon

Judging-committee: Annick Hubin, Jean Vereecken, Steve Vanlanduit, Lennart Ljung (Linköping University), Jan Swevers (KUL), Yves Rolain

PHD61. **GSM-based Positioning: Techniques and Application**

Nico Deblauwe

Doctoral Dissertation, Vrije Universiteit Brussel, June 2008

Promoters: Leo Van Biesen, Prof. Dr. Claudia Linnhoff-Popien (Ludwig-Maximilians-Univ. Munchen)

Judging-committee: Dirk Lefeber, Rik Pintelon, Peter Schelkens, Wendy Van Moer, Luc Vandendorpe (Universit Catholique de Louvain), Luc Martens (Universite Gent), Fredrik Gustafsson (Linköping University)


Anna Marconato

Doctoral Dissertation, Vrije Universiteit Brussel - Università degli Studi di Trento, March 2009

Promoters: Prof. Dario Petri, Johan Schoukens, Bruno Caprile

Judging-committee: Annick Hubin, Gerd Vandersteen, Michel Verleysen (UCL), Davide Anguita (University of Genova), Anne Nowé

PHD63. **A framework for the analysis and modelling of substrate noise**

Stephane Bronckers

Doctoral Dissertation, Vrije Universiteit Brussel, June 2009

Promoters: G. Van der Plas, G. Vandersteen

Judging-committee: A. Hubin, voorzitter, R. Pintelon, P. Wambacq, M. Nagat, (Kobe University, Japan), F.J. Climent, (Coupling Wave Solutions, France), W. Schoenmaker (Magwel, Belgium)
PHD64. Identification and use of nonparametric noise models extracted from overlapping subrecords
Kurt Barbé
Doctoral Dissertation, Vrije Universiteit Brussel, September 2009
Promoters: Rik Pintelon, Johan Schoukens
Judging-committee: Annick Hubin, Patrick Guillaume, Gerd Vandersteen, Lennart Ljung (Linköping University), Jérôme Antoni (Univ. de Technologie de Compiègne), Joos Vandewalle (KULeuven), Steve Vanlanduit

PHD65. Model Fitting in Frequency Domain Imposing Stability of the Model
László Balogh
Doctoral Dissertation, Vrije Universiteit Brussel, October 2009
Promoters: Rik Pintelon, István Kollár (TUBudapest)
Judging-committee: Johan Schoukens, Patrick Guillaume, Joos Vandewalle (KULeuven), Steve Vanlanduit, Barnabás Garay (TUBudapest)

PHD66. CMOS building blocks for 60 GHz Phased-Array receivers
Karen Scheir
Promoters: Piet Wambacq, Yves Rolain)
Judging-committee: A. Hubin, R. Pintelon, G. Vandersteen, J. Long (TUDelft, Nederland), K. Halonen (Helsinki University of Technology, Finland), C. Debaes

PHD67. Localization in wireless networks and co-existence of broadband services
Mussa Bshara
Doctoral Dissertation, Vrije Universiteit Brussel, June 2010
Promoter: Leo Van Biesen
Judging-committee: J. Tiberghien, R. Pintelon, P. Schelkens (IBBT), F. Gustafsson (Linkoping Universitet), G. Vandersteen, P. Boets (Alcatel-Lucent-bell), L. Vandendorpe (UCL)

PHD68. Advanced calibration and Instrumentation setups for nonlinear RF devices
Liesbeth Gommé
Doctoral Dissertation, Vrije Universiteit Brussel, August 2010
Promoter: Yves Rolain
Judging-committee: A. Hubin, R. Pintelon, G. Vandersteen, K. Godfrey (University of Warwick), D. Barataud (University of Limoges), M. Vanden Bossche (NMDG Engineering)

PHD69. A Bayesian Model To Construct A Knowledge Based Spatial Decision Support System For The Chaguana River Basin
Indira Nolivos Alvarez
Doctoral Dissertation, Vrije Universiteit Brussel, October 2010
Promoters: Leo Van Biesen, Pilar Cornejo (ESPOL, Ecuador)
Judging-committee: J. Tiberghien, R. Pintelon, W. Bawens, Pedro Girao (Universidade Tcnica de Lisboa), Rony Swennen (KUL), Ann Now

PHD70. Best Linearized models for RF systems
Koen Vandermot
Doctoral Dissertation, Vrije Universiteit Brussel, October 2010
Promoter: Yves Rolain
Judging-committee: W. Bawens, R. Pintelon, G. Vandersteen, D. Vanhoenacker (UCL), T. Dhaene (Universiteit Gent), M. Vanden Bossche (NMDG Engineering)

PHD71. Time series reconstruction of environmental proxy records
Veerle Beelaerts
Doctoral Dissertation, Vrije Universiteit Brussel, January 2011
Promoter: Rik Pintelon, Frank Dehairs
Judging-committee: W. Bawens, H. Terryn, J. Schoukens, J. Vandewalle (KUL), G. Munhoven (Université de Liège), D. Paillard (Lab. des Sciences du Climat et de l'environnement, Centre de Saclay, France), M. Elskens

PHD72. Multirate Cascaded ΔS Converters for Wireless Applications
Lynn Bos
Doctoral Dissertation, Vrije Universiteit Brussel, January 2011
Promoters: G. Vandersteen, Dr, ir. J. Ryckaert
Judging-committee: P. Guillaume, H. Terryn, P. Wambacq, P. Rombouts (Universiteit Gent), K. Makinwa (Delft University of Technology), B. Murmann (Stanford University)

PHD73. Use and modeling of overtone resonances in FBAR resonators operating at RF frequencies
Mohamed Reda Amin El-Barkouky
Doctoral Dissertation, Vrije Universiteit Brussel, January 2011
Promoters: Y. Rolain, P. Wambacq
Judging-committee: D. Lefeber, H. Terryn, G. Vandersteen, B. Otis (University of Washington, Seattle, USA), J. Vandewalle (KUL)

PhD74. Nonlinear and Dynamical Models for Temperature Reconstructions from Multi Proxy Data In Bivalve Shells
Maite Bauwens
Doctoral Dissertation, Vrije Universiteit Brussel, March 2011
Promoters: Johan Schoukens and Frank Dehaes
Judging-committee: Alan Wanamaker (Iowa State University, USA), Luc André (ULB-MRAC), Fjo De Ridder, Rik Pintelon, Willy Baeyens, Mark Elskens

PhD75. Reflectometric Analysis of Transmission Line Networks
Carine Neus
Doctoral Dissertation, Vrije Universiteit Brussel, March 2011
Promoters: Leo Van Biesen, Yves Rolain
Judging-committee: Annick Hubin, Ludwig De Loch, Patrick Boets (Alcatel-Lucent, Belgium), Luc Martens (U-Gent), Tomas Nordström (FTW Telecommunication Research Center Vienna, Austria)

PhD76. Frequency Domain Measurement and identification of Linear, Time-varying Systems
John Lataire
Doctoral Dissertation, Vrije Universiteit Brussel, March 2011
Promoter: Rik Pintelon
Judging-committee: Jérome Antoni (Université Compiègne, France), Lennart Ljung (University of Linköping, Sweden), Paul Van den Hof (Delft University of Technology, The Netherlands), Johan Schoukens, Patrick Guillaume, Herman Terryn, Steve Vanlanduit.

PhD77. Nonlinear dynamic systems: blind identification of block-oriented models, and instability under random inputs
Vanbeylen Laurent
Promoters: Rik Pintelon, Johan Schoukens
Judging-committee: Hugo Sol, Herman Terryn, Gerd Vandersteen, Adrian Wills (University of Newcastle, Australia), Johan Suykens (KULeuven), Rodolphe Sepulchre (Université de Liège), Patrick Guillaume

PhD78. Study of 3D position determination of the interaction point in monolithic scintillator blocks for PET
Zhi Li
Promoters: Stefaan Tavernier, Gerd Vandersteen
Judging-committee: Johan Schoukens, Michel Defrise, Karl Ziemons (University of Aachen, Germany), Jose Perez (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain)

PhD79. Some practical applications of the best linear approximation in nonlinear block-oriented modelling
Lieve Lauwers
Promoter: Johan Schoukens
Judging-committee: Gert Desmet, Herman Terryn, Kurt Barbé, Keith Godfrey (University of Warwick), Joos Vandewalle (KULeuven), Steve Vanlanduit

PhD80. Design and evaluation of channel models for DSL applications
Wim Foubert
Doctoral Dissertation, Vrije Universiteit Brussel, November 2011
Promoters: Leo Van Biesen and Yves Rolain

PhD81. Digital Basedband Modeling and Correction of Radio Frequency Power Amplifiers
Per Landin
Doctoral Dissertation, KTH School of Electrical Engineering, Stockholm, Sweden - Vrije Universiteit Brussel (cotutelle), June 2012
Promoters: Wendy Van Moer
Judging-committee:

PhD82. Frequency Domain Based Performance Optimization of Systems with Static Nonlinearities
David Rijlaarsdam
Promoters: Maarten Steinbuch (TUE) - Johan Schoukens, P.W.J.M. Nuij (co-promoter TUE)

**PhD83. Tackling two drawbacks of polynomial nonlinear state-space models**
Van Mulders Anne
Doctoral Dissertation, Vrije Universiteit Brussel, June 2012
Promoter: Johan Schoukens
Jury: Hugo Sol, Herman Terryn, Gerd Vandersteen, Håkan Hjalmarsson (KTH), Thomas Schönn (Linköping Sweden), Jan Swevers (KUL), Patrick Guillaume

**PhD84. Signal Shaping and Sampling-based Measurement Techniques for Improved Radio Frequency Systems**
Charles Nader
Doctoral Dissertation, University of Gävle, Sweden - Vrije Universiteit Brussel (cotutelle), August 2012
Promoters: Prof. Nilas Björsel (University of Gävle); Prof. Wendy Van Moer (Vrije Universiteit Brussel)
Jury: Prof. Heidi Ottevaere, Prof. Herman Terryn, Prof. Kurt Barbé, Dr. Lee Barford (Agilent Technologies); Prof. Håkan Hjalmarsson (KTH Royal Institute of Technology); Prof. Gurvinder Virk Singh (University of Gävle); Dr. Marc Vanden Bossche (NMDG)

**PhD85. Modelling and Optimization of Algorithms for Multiuser Multicarrier systems**
Cordova Junco Hernandez Xavier
Doctoral Dissertation, Vrije Universiteit Brussel, October 2012
Promotor: Leo Van Viesen

**PhD86. Identification in Nuclear and Thermal Energy. Moderator Temperature Coefficient Estimation via Noise Analysis and Black-Box Modeling of Heat Transfer**
Griet Monteye
Doctoral Dissertation, Vrije Universiteit Brussel, April 2013
Promoter: Gerd Vandersteen, Peter Baeten
Jury: Christophe Demazière (Chalmers University of Technology, Sweden), Saqib Javed (Chalmers University of Technology, Sweden), Jan Swevers (KUL), Steve Vanlanduit, Johan Deconinck, John Lataire, Johan Schoukens

**PhD87. Closing the design gap between system-level and component-level Electro Static Discharge (ESD)**
Mirko Scholz
Doctoral Dissertation, Vrije Universiteit Brussel, May 2013
Advisors: Gerd Vandersteen, Dimitri Linten (IMEC)
Jury: Maarten Kuijk, Johan Deconinck, Piet Wambacq, Dr. Vladislav Vashchenko (Maxim IC), Harald Gossner (Intel)

**PhD88. Study of the Best Linear Approximation of Nonlinear Systems with Arbitrary Inputs**
Wong, Hin Kwan Roland
Doctoral Dissertation, Vrije Universiteit Brussel - University of Warwick, UK (co-tutelle), June 2013
Advisors: Prof. em. Dr. Keith R. Godfrey (University of Warwick), Prof. Dr. ir. Johan Schoukens, Prof. Dr. Nigel G. Stocks (University of Warwick)
Jury: Steve Vanlanduit, Tadeusz Dobrowiecki (Budapest University of Technology and Economics), Johan Deconinck, Gerd Vandersteen, Peter R. Jones (University of Warwick), Jérôme Antoni (Université de Lyon)

**PhD89. Frequency Domain Measurement and Identification of Weakly Nonlinear Time-Periodic Systems**
Ebrahim Louarroudi
Doctoral Dissertation, Vrije Universiteit Brussel, September 2014
Advisors: Rik Pintelon and John Lataire
Jury: Jérôme Antoni (University de Lyon, France), Keith Godfrey (University of Warwick, UK), Frans van der Helm (Delft University of Technology, Nederland), Ivan Markovsky, Steve Vanlanduit, Johan Deconinck, Gerd Vandersteen

**PhD90. Glucose Estimation at Physiological Levels Employing Electrochemical Impedance Spectroscopy and Gas Sensors**
Oscar Javier Olarte Rodríguez, Vrije Universiteit Brussel, December 2014
Advisors: Wendy Van Moer, Yves Van Ingelgem, Kurt Barbé
Jury: Clara Jonascu (Ghent University), Sergio Rapuano (University of Sannio, Italy), Jose Chilo (Högskolan i Gävle, Sweden), Chris van Schravendijk (Diabetes Research Center VUB), Heidi Ottevaere, Johan Deconinck
5.12  THESIS TOT HET BEHALEN VAN HET AGGREGAAT VAN HET HOGER ONDERWIJS

PhD1.  System Identification. A Frequency Domain Modeling Approach
Johan Schoukens
Geaggregeerde van het hoger onderwijs, Vrije Universiteit Brussel, 1991
Judging-committee: G. Maggetto (VUB), G. Baron (VUB), G. Vansteenkiste (VUB), P. Eykhoff (TU Eindhoven), A. van den Bos (TU Delft), J. Vandewalle (KUL), M. Gevers (UCL)
Promoters: J. Renneboog (VUB), A. Barel (VUB)

PhD2. Frequency Domain Identification of Linear Time Invariant Systems
Rik Pintelon
Geaggregeerde van het hoger onderwijs, Vrije Universiteit Brussel, 1994
Judging-committee: G. Maggetto (VUB), A. Cardon (VUB), G. Baron (VUB), P. Eykhoff (TU Eindhoven), M. Gevers (UCL), A. van den Bos (TU Delft), J. Vandewalle (KUL), G. Van Steenkiste (RUG)
Promoter: A. Barel (VUB)

5.13  DOCTOR OF SCIENCE

PhD1. Frequency Domain System Identification: A Mature Modeling Tool
Rik Pintelon
Doctor of Science, University of Warwick, October 20, 2014

PhD2. System Identification in a Nonlinear Environment
Johan Schoukens
Doctor of Science, University of Warwick, October 20, 2014
Getting to the department ELEC of the "Vrije Universiteit Brussel"

6. Location of the university (VUB) and the dept. ELEC

6.1 ARRIVAL BY CAR:

Take the "Ring" and exit at the crossing with the motorway E411 direction centre of Brussels. At the end of the motorway, take the viaduct (go straight on), and at the second traffic lights, turn on right ("Triomflaan"), the VUB is situated on the left side of this road, starting from entrance 6 (see next map).

6.2 FROM THE BRUSSELS NATIONAL AIRPORT AT ZAVENTEM:

Brussels International Airport is at Zaventem, 14 km from the city centre.

- Information can be obtained by phone: Tel +32 2 753 42 21 / +32 2 723 31 11
- Flight information: Tel +32 900 70 000 (7 a.m. - 10 p.m.)
- www.brusselsairport.be

From the airport, every 20 minutes the rail shuttle quickly takes you to the North Station in the centre of Brussels. At the North Station ("Bruxelles Nord"), you take the train to Etterbeek (direction Etterbeek or Louvain La Neuve) and get off the train in Etterbeek, which is 10 min. walking distance
from the VUB. You only pay € 6.00 for a standard jump ticket (a taxi or cab from airport to the University is about € 50.00).

More information and timetables of the Belgian railways: www.b-rail

6.3 FROM BRUSSELS SOUTH AIRPORT (CHARLEROI)

Situated to the south of Brussels, approximately 60 km away, Brussels-South Charleroi airport mainly houses low-cost airlines. www.charleroi-airport.com

A bus links Charleroi Brussels-South and the Gare du Midi railway station in Brussels more than 20 times a day.

The timetables are organised to coincide with Ryanair airline flights.

- Brussels to Charleroi: The shuttle departure point is situated at the junction of rue de France and rue de l'Instruction (follow "Thalys" exit at the Gare du Midi station).
- Charleroi to Brussels: shuttle departs 30 minutes after the Ryanair airline flight arrives at the airport. One-way ticket fare: 10.00 € (tickets are sold inside the shuttle)

6.4 ARRIVAL BY TRAIN:

Change in "Bruxelles Nord" and take the train to Etterbeek (direction Etterbeek or Louvain La Neuve).

Info timetables: www.belgianrail.be/en

6.5 ARRIVAL BY SUBWAY (€ 2,00/MOBIB-TICKET):

Take line 5 direction "Hermann-Debroux" and get off at "Petillon", which is also 10 min. walking distance from the VUB.

More information about Brussels subway: www.stib.be

The dept. ELEC is located in building K, 6th floor.
Address: Vrije Universiteit Brussel, Department ELEC, Pleinlaan 2, Building K, 6th floor, B-1050 Brussels, Belgium

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Telefax: +32 (0)2 629 28 50 Ann.Pintelon@vub.ac.be
www-environment: wwwir.vub.ac.be/elec/ Annick.Schreyers@vub.ac.be