ERNSI Workshop 2015: Program

Version: 2015-09-15

Sunday, September 20

19:00 **Dinner**

Monday, September 21

Breakfast (served from 6:30)

(7:15 **Running session** [Chair: Marion Gilson])

9:00 **Welcome**

9:05 **N2SID: Structured subspace identification of innovation models**, Michel Verhaegen (Delft University of Technology) [Chair: Tomas McKelvey]

9:35 **Combining kernel-based methods and the EM method for structured system identification**, Giulio Bottegal (KTH Royal Institute of Technology) [Chair: Tomas McKelvey]

10:05 **Poster teasers**

10:20 **Coffee**

10:40 **Poster session A**

12:00 **Lunch**

13:30 **Invited talk: System identification taking off – Applications to rotorcraft control**, Ola Härkegård (Saab Aeronautics) [Chair: Martin Enqvist]

14:15 **Time series inference with nonlinear dynamics and filtering for control**, Rowan Thomas McAllister (University of Cambridge) [Chair: Martin Enqvist]

14:45 **Poster teasers**

15:00 **Coffee**

15:15 **Poster session B**

16:45 **Challenging ourselves: Three benchmarks for nonlinear system identification**, Maarten Schoukens (Vrije Universiteit Brussel) [Chair: Alessandro Chiuso]

17:15 **A critical view on benchmarks based on randomly generated systems**, Cristian R. Rojas (KTH Royal Insitute of Technology) [Chair: Alessandro Chiuso]

17:45–18:15 **NucID: A direct approach to SYSID using nuclear norms**, Kristiaan Pelckmans (Uppsala University) [Chair: Alessandro Chiuso]

19:00 **Dinner**

Tuesday, September 22

Breakfast (served from 6:30)

(7:15 **Running session** [Chair: Marion Gilson])

9:00 **Tutorial: From Volterra series through block-oriented approach to Volterra series**, Pawel Wachel (Wroclaw University of Technology) [Chair: Bo Wahlberg]

9:45 **Poster teasers**

10:00 **Coffee**

10:15 **Poster session C**

11:30 **Sparse plus low rank network identification: A nonparametric approach**, Mattia Zorzi (University of Padova) [Chair: Marion Gilson]

12:00: **Nonlinear identification of individualized drug effect models of the neuromuscular blockade in anesthesia**, Alexander Medvedev (Uppsala University) [Chair: Marion Gilson]

12:30-13:30 **Lunch**

14:00 **Social program** (a visit to the Grimeton Radio Station)

18:30 **Drinks**

19:00 **Dinner**

Wednesday, September 23

Breakfast (served from 6:30)

(7:15 **Running session** [Chair: Marion Gilson])

9:00 **Tutorial: Average risk minimization in impulse response estimation**, Håkan Hjalmarsson (KTH Royal Institute of Technology) [Chair: Paul Van den Hof]

9:45 **Coffee (and check-out if not earlier)**

10:15 **Maximum entropy vector kernels for MIMO system identification**, Alessandro Chiuso (University of Padova) [Chair: Carl Rasmussen]

10:45 **Poster teasers**

11:00 **Poster session D**

12:30-13:30 **Lunch**

Abstracts: Talks

N2SID: Structured subspace identification of innovation models

Michel Verhaegen (Delft University of Technology, The Netherlands)

Abstract: The N2SID subspace identification scheme was propsed in [1]. This subspace method solves the identification of the innovation model from input-output data without the use of instrumental variables. As it allows to incorporate important structural information on the matrices in the so-called data-equation it has the potential to improve the accuracy of the estimates under harsh experimental conditions, such as e.g. the case in identifying dynamical systems where the ratio between model order and length of the data sequences is close to one.

A key question addressed in this short presentation is whether the Markov parameter structure in unknown matrices in the data equation needs to be taken into consideration in guaranteeing uniqueness of the solution. This question is addressed for the original rank minimization problem.

When the answer to this question is yes, it means o.a. that the convexity of the N2SID is destroyed. Let us see what the answer is.

References:

[1] M. Verhaegen and A. Hansson, Nuclear Norm Subspace Identification (N2SID) for short data batches, 19th IFAC World Congress, SA, 2014.

Combining kernel-based methods and the EM method for structured system identification

Giulio Bottegal (KTH Royal Institute of Technology, Sweden)

Abstract: Recent developments in system identification have brought attention to regularized kernel-based methods for linear dynamic systems. In this talk, we discuss on how to employ these methods in problems involving structured identification and input/output uncertainties. Examples are:

- Block-oriented cascade linear and nonlinear identification
- Unknown initial conditions
- Blind and semi-blind identification
- Outliers on noise

In order to deal with these uncertainties we adopt an empirical Bayes approach. This requires solving maximum likelihood/a-posteriori problems that may look complex since typically they are non-convex and involve a large number of unknowns. To overcome these difficulties, we show how to employ the Expectation-Maximization method to design iterative solution schemes consisting of very fast and simple update rules for the parameters characterizing the system identification problem.

Invited talk: System identification taking off – Applications to rotorcraft control

Ola Härkegård (Saab Aeronautics)

Abstract: In recent years I have been involved in the development of the Skeldar system, an unmanned helicopter designed for military and civil surveillance applications, at land and over sea. In this talk I will give an overview of the development of the Skeldar flight control laws, and in particular highlight the important role that system identification has played. Helicopters are intriguing dynamic systems without low level of built-in stability and with cross-couplings that prove difficult to model physically. With high control requirements and readily available flight data, the stage is set for system identification to prove its worth.

Time series inference with nonlinear dynamics and filtering for control

Rowan Thomas McAllister, Carl Edward Rasmussen (University of Cambridge, UK)

Abstract: We present a data-efficient method to learn control of nonlinear, underactuated systems with noisy sensors from scratch (i.e. no prior system identification). Our work extends the model-based reinforcement leaning framework of PILCO (Deisenroth & Rasmussen, 2011) to consider how filtering the state observations affects the expected loss, used to optimise the controller.

System identification with little data implies a large space of plausible systems consistent with the data. Methods that identify a single model from a large possible set suffer from model-bias, slowing the learning progress. Probabilistic models can help avoid model bias by considering the full distribution of plausible models. The PILCO framework uses a probabilistic model to consider system uncertainty when simulating trajectories in order to optimise a controller. Doing so, it is more likely to collect data in promising areas of the state space, resulting in data-efficient learning. Good simulators must reflect reality. Thus, unlike model predictive control, closed loop control is simulated, precisely because closed loop control is executed in reality. By re-training the dynamics model and re-optimising the controller between task trials, PILCO learns to control a system after a low number of trials.

This research extends PILCO by additionally simulating the filtering process. By simulating filtering we optimise the controller with respect to filtered observations. Doing so, we achieve significantly higher performance than simply combining a filter with a controller optimised by the original (unfiltered) framework. The reason is our simulator is faithful to the reality of the controller using filtering observations as input. We test our method on the cart-pole system, which requires nonlinear control to balance a free-spinning pendulum upright (when the pendulum begins hanging downwards). We show how our method learns to control the cart-pole with noisy observations in just five trials, where each trial lasts 5 seconds.

Challenging ourselves: Three benchmarks for nonlinear system identification

Maarten Schoukens (Vrije Universiteit Brussel, Belgium), **Jean-Philippe Noël** (Université de Liège, Belgium)

Abstract: This talk presents three new benchmarks for nonlinear system identification: a Bouc-Wen hysteretic system, a Wiener-Hammerstein system with process noise, and a cascaded tank system. They are believed to feature state-of-the-art challenges in the field, namely dynamic nonlinearities, process noise in nonlinear systems and short data records respectively.

The prime goal of these three benchmarks is to advance the current knowledge in nonlinear system identification by fostering informal exchange of ideas and formal collaborations between the system identification, the mechanical and the machine learning communities. These three communities have developed over the years various and numerous nonlinear modeling approaches driven by specific backgrounds, constraints and end-uses. Moreover, they generally face different challenges and thus focus on different aspects of the modeling problem. This is why we believe that, by promoting interaction, significant benefit can be mutually gained.

To achieve this goal, we organize a three-day research workshop in spring 2016 at the Vrije Universiteit Brussel, Brussels, Belgium. This workshop will be structured around the three proposed benchmark systems and will consist of keynote lectures, plenary presentations, and free discussion sessions.

The participants will be able to apply their self-designed signals to the Bouc-Wen hysteretic system and the Wiener-Hammerstein system, the cascaded tank system comes with a fixed data record. The data records used for the different modeling approaches will be made available on an online repository such that they remain accessible in the future to test newly developed modeling approaches.

More info on: `http://homepages.vub.ac.be/~mschouke/benchmark2016.html`

A critical view on benchmarks based on randomly generated systems

Cristian R. Rojas, Patricio E. Valenzuela (KTH Royal Insitute of Technology, Sweden), and **Ricardo A. Rojas** (Universidad Técnica Federico Santa María, Chile)

Abstract: In data-based modelling communities, such as system identification, machine learning, signal processing and statistics, benchmarks are essential for testing and comparing old and new techniques for the estimation of models. During the last years, it has become customary in system identification to rely on data sets built from randomly generated systems. In this contribution we discuss the implications of this practice, in particular when using data sets generated with the MATLAB command "drss", and advocate the cautious use of comparisons based on these benchmarks.

NucID: A direct approach to SYSID using nuclear norms

Kristiaan Pelckmans (Uppsala University, Sweden)

Abstract: This talk presents new findings for using the nuclear norm for identification of LTI systems from experiments. Both the conceptual setting, algorithmic issues, as well as various extensions are discussed. By introducing experimental results of related techniques, we hope to incite the discussion about the role of convex optimization in system identification.

Tutorial: From Volterra series through block-oriented approach to Volterra series

Przemyslaw Sliwinski, Pawel Wachel (Wroclaw University of Technology, Poland)

Abstract: In the talk we present several nonparametric identification algorithms based on the block-oriented approach, that is, based on assumption that the structure of the system assembled from static nonlinear and dynamic linear blocks is known. When put in historical perspective, they were results of the-then serious deficiencies of the Volterra approach, which required large datasets and supercomputers. Nonparametric block oriented algorithms, offered rather fast algorithms instead and hence were not only attractive from the theoretical but also from practical vantage point. They are nonparametric in the sense that the a priori information about the system blocks is minimal (e.g. the nonlinear blocks can virtually be any function while the linear dynamics can be any stable LTI system). In spite of that they are however somehow specific - that is - they are designed for specific system structures and usually valid for a white-noise input only.

Recent developments in optimization and high-dimension statistics allowed to revive the Volterra series approach and make it again competitive with the block-oriented one. In particular, we present our recent development, an effective modelling algorithm based on convex optimization.

Sparse plus low rank network identification: A nonparametric approach

Mattia Zorzi and Alessandro Chiuso (University of Padova, Italy)

Abstract: Modeling and identification of high-dimensional stochastic processes is ubiquitous in many fields. In particular, there is a growing interest in modeling stochastic processes with simple and interpretable structures. In many applications, such as econometrics and biomedical sciences, it seems natural to describe each component of that stochastic process in terms of few latent variables, which are not accessible for observation, and possibly of few other components of the stochastic process. These relations can be encoded in graphical way via a structured dynamic network, referred to as “sparse plus low-rank (S+L) network” hereafter. The problem of finding the S+L network as well as the dynamic model can be posed as a system identification problem. In this paper, we introduce two new nonparametric methods to identify dynamic models for stochastic processes described by a S+L network. These methods take inspiration from regularized estimators based on recently introduced kernels (e.g. "stable spline", "tuned-correlated" etc.). Numerical examples show the benefit to introduce the S+L structure in the identification procedure.

Nonlinear identification of individualized drug effect models of the neuromuscular blockade in anesthesia

Olov Rosén, Alexander Medvedev, Margarida M. Silva (Uppsala Universitym Sweden)

Abstract: Closed-loop drug administration is performed by a feedback controller that, while coping with process disturbances and uncertainty, keeps the patient response around a pre-set target level. To guarantee the safe operating envelope of the closed-loop drug delivery system, controller design for performance and robustness is typically based on a mathematical model of the plant. Minimally parameterized Wiener models comprising a linear dynamic block and a smooth static output nonlinearity have been shown to accurately capture the patient-specific pharmacokinetics and pharmacodynamics in closed-loop drug administration. The present work compares the performance of three nonlinear system identification algorithms: an extended Kalman filter (EKF), a conventional particle filter (PF), and a PF making use of a orthonormal basis to estimate the probability density function from the particle set. A database of patient models estimated under PID-controlled neuromuscular blockade during general anesthesia is utilized, along with the clinical measurements. The bias and variance of the estimated models are related to the computational complexity of the identification algorithms, highlighting the superiority of the PFs in this safety- critical application. The distance to a bifurcation phenomenon leading to nonlinear oscillations of the Wiener model under PID feedback is also evaluated. It is demonstrated that the EKF, an identification technique based on linearization, yields biased parameter estimates and thus introduces superfluous uncertainty in the drug administration system design.

Tutorial: Average risk minimization in impulse response estimation

Håkan Hjalmarsson (KTH Royal Institute of Technology, Sweden)

Abstract: The use of new kernels, e.g. the stable spline kernel, in combination with the Empirical Bayes (EB) approach has lead to very potent algorithms for estimating dynamical systems. In this talk we take a frequentistic approach and consider the problem of determining the so called hyperparameters from a Mean Square Error perspective. This leads to a framework where first the rank-1 matrix obtained by squaring (in a matrix sense) the impulse response of the

system has to be estimated from data, and then the hyperparameters are found by minimizing an estimate of the MSE. We show that a range of existing methods can be interpreted as different approaches to estimate the rank-1 matrix, e.g. Stein's Unbiased Risk Estimate as well as the aforementioned EB approach. This framework also allows us to show that when the kernel itself is rank-1 and linearly parametrized, the EB-approach leads to an estimator of James-Stein type, i.e. a shrinkage estimator.

Maximum entropy vector kernels for MIMO system identification

Alessandro Chiuso (University of Padova, Italy)

Abstract: Recent contributions in linear system identification have introduced regularized kernel-based methods, which in some situations have proved to be advantageous w.r.t classical parametric methods. In the system identification context, typical formulations exploit an

l2-type regularization which accounts for the stability and smoothness of the impulse response to be estimated. In this paper, we adopt maximum entropy arguments to derive a new type of

l2-regularization which results in a vector kernel. It appears to be particularly suited for the identification of MIMO systems, since it is designed in order to control the rank of the block Hankel matrix built with Markov coefficients, and hence the complexity of the estimated system. A special formulation of the penalty we derive gives back the standard nuclear norm penalty. We combine this Hankel-based regularization with the standard l2-type regularization adopted in system identification and we design an algorithm which iteratively updates the hyper-parameters defining the two types of kernel. The update is performed through Marginal Likelihood maximization: to this aim, we adopt a Scaled Gradient Projection algorithm, specifically adjusted to the problem we are considering, which is proved to be computationally cheaper than other first and second order optimization methods. The effectiveness of the identification technique we propose is confirmed by several Monte-Carlo studies.

Abstracts: Poster session A

Chair: Ylva Jung

A1: Subspace-based model identification with equality constraints

Guillaume Mercère (University of Poitiers, France) and **Ivan Markovsky** (Vrije Universiteit Brussel, Belgium)

Abstract: With this poster, we address the problem of incorporating prior information in subspace-based model identification. More precisely, by assuming that prior knowledge on the system to identify (like static gains, zero transfer functions,...) can be translated into specific equality constraints, we develop a new data-driven algorithm by following the well-known behavioral approach. One of the main reasons why we develop such a constrained subspace-based technique can be related to practical considerations. It is well-known that the identified model quality highly depends on the information contained into the data-sets. When the available data-set is poor (poor excitation, small number of samples), we suggest improving the quality of the estimated model by explicitly incorporating prior information about the system into a new susbpace-based identification algorithm. In this contribution, we mainly focus on the estimation as well as the use of the Markov parameters. These parameters can be indeed easily linked to prior information and can be considered as the keystone of subspace-based model identification. These developments are illustrated through the description of a new constrained subspace-based model identification algorithm as well as simulation examples.

A2: A polynomial nonlinear state-space Matlab toolbox

Koen Tiels (Vrije Universiteit Brussel, Belgium)

Abstract: A polynomial nonlinear state-space (PNLSS) model can capture many different nonlinear behaviors and has been successfully applied in a large range of applications. Moreover, the PNLSS model structure can be identified from both periodic and aperiodic data. At the poster, I would like to discuss on a PNLSS Matlab Toolbox that will be developed and made publicly available. New features will include the possibility to impose constraints (e.g. to impose structure) and the possibility to capture non-polynomial nonlinearities.

A3: Identification of linear parameter-varying state-space models with static and affine dependency

Pepijn B. Cox (Eindhoven University of Technology, The Netherlands)

Abstract: The linear parameter-varying (LPV) modelling paradigm offers an attractive parsimonious model class that can capture moderate nonlinearities

or time-varying effects of a data generating system. Hence, recently, the LPV model class has became popular for many control synthesis methods, in particular LPV state-space (SS) models with affine dependence on the scheduling parameter. However, current, identification approaches for LPV-SS models suffer heavily from the curse of dimensionality, are computationally expensive and/or depend on over-restrictive approximation of the measured signal behaviours. Therefore, to fully exploit the capabilities of the LPV modelling framework, it is crucial to find fast and efficient LPV-SS identification methods. We tackle the problem by combining state-of-the-art of LPV input-output (IO) identification methods, with LPV-IO to LPV-SS realization, and maximum likelihood refinement steps. This results in an efficient modular approach containing the following three steps: 1) estimate the Markov coefficient sequence of the underlying system using correlation analysis or Bayesian identification of the multiple-input multiple-output impulse response functional, then 2) create an LPV-SS realization from the estimated coefficients by using an efficient Ho-Kalman like method, and 3) refine the LPV-SS model estimate from a maximum-likelihood point of view by gradient-based or expectation-maximization optimization.

A4: Nonparametric estimation of Hammerstein systems

Riccardo Sven Risuleo, Giulio Bottegal and Håkan Hjalmarsson (KTH Royal Institute of Technology, Sweden)

Abstract: The Hammerstein nonlinear system is a time invariant block structured nonlinear system, where the input is first transformed by a static nonlinearity and then is fed to a linear time invariant dynamical system. Using kernel regression, we model the impulse responses of the predictor of the linear system and the nonlinear input transformation as a Gaussian processes with suitable kernels. We propose a joint maximum-a-posteriori-maximum-likelihood estimator to identify the kernel hyperparameters and the nonlinear transformation from the data marginal likelihood, where the predictor impulse responses have been integrated out. The predictor impulse responses are then found using the hyperparameters in the Bayesian minimum variance estimates. To solve the marginal likelihood maximization, we propose an iterative scheme based on the Expectation-Conditional-Maximization method, that results in a set of simple update rules for the problem unknowns.

A5: Classical vs. Bayesian methods for linear system identification: point estimators and confidence sets

Diego Romeres, Giulia Prando, Gianluigi Pillonetto and Alessandro Chiuso (University of Padova, Italy)

Abstract: The work compares the standard parametric system identification approaches with the recently developed non-parametric approaches, relying on Bayesian estimation. The comparison is carried out both in terms of closeness

between the point estimates returned by the above-mentioned approaches and the true system and in terms of the confidence sets that can be built around the point estimates. The goodness of a certain confidence set is measured by evaluating both its size and whether it contains or not the true system.

Among the parametric approaches, our work considers the PEM method, equipped with the BIC criterion for model order selection or with an oracle which has the unrealistic knowledge of the true system. On the other hand, two different Bayesian approaches are considered: the so-called Empirical Bayes and the Full Bayes, which is obtained through an Adaptive Metropolis algorithm.

In the Monte-Carlo simulations we conduct, the Bayesian approaches not only outperform the para- metric ones in terms of goodness of the point estimators but they also provide better approximations for the uncertainty regions.

A6: Nonparametric regularized identification and Bayesian learning of nonlinear state space models using particle Gibbs

Andreas Svensson, Thomas B. Schön (Uppsala University, Sweden), **Arno Solin, Simo Särkkä** (Aalto University, Finland)

Abstract: We are concerned with nonparametric system identification (i.e., learning without a priori assumptions on parametrizations) of nonlinear state space models. By using a basis function expansion of the unknown nonlinear functions, we obtain a model nonlinear in the states but linear in the parameters. By using the particle Gibbs with ancestor sampling, we can learn such models efficiently. By a relatively small modification of the learning algorithm, we can perform classical maximum likelihood identification, L2-regularized maximum likelihood identification, as well as fully Bayesian learning. In the fully Bayesian case, we can learn Gaussian process state space models, and also show results on real data competitive to classical nonlinear system identification methods.

A7: Comparing the regularized least squares and the convex constraint least squares methods on Volterra series estimation

Przemyslaw Sliwinski*, Georgios Birpoutsoukis, Pawel Wachel*, Anna Marconato**, Johan Schoukens**** (Wroclaw University of Technology, Poland*, Vrije Universiteit Brussel, Belgium**)

Abstract: The problem of nonlinear dynamic system identification/modelling, in the case when the Volterra series is used as a model structure, is tackled. Two different methods, namely the regularized least squares and the convex constrained least squares methods are described and compared. The results obtained for the Wiener-Hammerstein benchmark system indicate that (1) both methods perform significantly better than the ordinary least squares and (2)

in spite of their different nature, they result in models characterized by similar accuracy.

A8: Gradient of regularization path for nuclear norm minimization

Niclas Blomberg, Cristian Rojas, Bo Wahlberg (KTH, Royal Institute of Technology, Sweden)

Abstract: The nuclear norm minimization heuristic is widely used for low-order model approximation, and involves a regularization parameter, λ. Our idea starts with computing the gradient of the regularization path, which is the optimal solution as a function of the regularization parameter, $f(\lambda^*)$. Assume we have an optimal solution $f(\lambda^*)$ for a particular λ^*. Then we can evaluate $f'(\lambda^*)$, which gives information about where the regularization path moves expressed in the estimation-variables.

The corresponding gradient for the LASSO problem is computed in [1] and it turns out to be constant on certain manifolds, implying that the regularization path is piecewise linear. It is, however, not the case for nuclear norm minimization. We believe there are several useful applications where the gradient comes in. Here, we focus on finding the value of λ giving the least validation cost, which alternatively can be obtained via the time-costly technique of cross validation.

[1] Osborne, M.R.; Presnell, B.; Turlach, B.A. A new approach to variable selection in least squares problems. IMA Journal of Numerical Analysis, 2000.

A9: Estimation of linear time varying systems using 2D regularization and B-splines

Péter Zoltán Csurcsia, Johan Schoukens, John Lataire (Vrije Universiteit Brussel, Belgium)

Abstract: In this work a nonparametric time domain estimation method of linear time-varying systems is presented. The challenge with time-varying systems is that the time-varying (two dimensional) impulse response functions are not uniquely determined from a single set of input and output signals - like in the case of linear time invariant systems. Due to this non-uniqueness, the number of possible solutions is growing quadratically with the number of samples. To decrease the degrees of freedom, user defined (adjustable) constraints will be imposed. In this particular case, it is imposed that the entire two dimensional impulse response function is smooth. This is implemented by a special two dimensional regularization and by a special B-spline technique.

A10: MOOSE2: Model based optimal input design toolbox for Matlab (function-based version)

Mariette Annergren (KTH Royal Institute of Technology, Sweden), **Christian A. Larsson** (Scania, previously KTH Royal Institute of Technology, Sweden)

Abstract: MOOSE2 is a MATLAB toolbox for solving applications-oriented input design problems. That is, how to optimally design the spectrum of excitation signals for system identification experiments to give estimated models that satisfy given pre-specified application and quality requirements, [1,2,3]. MOOSE2 is an independent extension of MOOSE [4]. The new version is based on functions and uses YALMIP [5] to construct the optimization problems, while the previous MOOSE toolbox was based on keywords and used CVX [6]. The function-based format allows for simple treatment of constraints imposed on spectra and powers of the signals present in the identification setup and constraints related to the estimated model's application and quality. The constraints have dedicated functions in MOOSE2 to enable a user-friendly implementation of applications-oriented input design problems. Examples of such constraints are frequency-wise upper bound on the input spectrum and an upper bound on the variance of the weighted relative error of the estimated model. MOOSE2 handles both MIMO and closed-loop identification where the controller is fixed, that is, it is not included in the closed-loop experiment design.

[1] Jansson, H., & Hjalmarsson, H. (2005). Input design via LMIs admitting frequency-wise model specifications in confidence regions. IEEE Transactions on Automatic Control, AC-50(10), 1534-1549.
[2] Bombois, X., Scorletti, G., Gevers, M., Van Den Hof, P. M. J., & Hildebrand, R. (2006). Least costly identification experiment for control. Automatica 42(10), 1651-1662.
[3] Hjalmarsson, H. (2009). System identification of complex and structured systems. European Journal of Control. 15(3), 275-310.
[4] Annergren, M. & Larsson, A. C. (2012). MOOSE: MOdel based Optimal input Signal dEsign. www.ee.kth.se/moose
[5] Löfberg, J. (2004). YALMIP: A Toolbox for Modeling and Optimization in MATLAB. Proceedings of the Computer Aided Control System Design Conference. 284-289.
[6] Grant, M., & Boyd, S. (2014). CVX: Matlab Software for Disciplined Convex Programming, version 2.1. www.cvxr.com/cvx

A11: Nonlinear system identification of the Li-ion battery cells for traction applications

Rishi Relan, Jean-Marc Timmermans, Johan Schoukens (Vrije Universiteit Brussel, Belgium)

Abstract: Lithium ion (Li-ion) batteries are attracting significant and growing interest because of their high energy and high power density render them an excellent option for energy storage, particularly in hybrid and electric vehicles as well as an ideal candidate for a wide variety of other applications. In order to develop a complete dynamic model of a lithium ion (Li-ion) battery's electrical behaviour, which is suitable for virtual-prototyping of battery-powered systems, accurate estimation of the state of charge (SoC) and state of health (SoH) is required. This in-turn depends on the quality of the models which are used for the estimation of these quantities. Hence, even before proceeding towards the modelling step, it is important to fully characterize and understand the electrical behaviour of the battery over its full operating range, so that a flexible and an accurate dynamic model can be developed. In this work, we will fully explore the battery's nonlinear operating regime to extract useful information based on the frequency domain non-parametric methodology. This advanced methodology allows us to characterize the battery short-term electrical behaviour, in terms of the presence of the nonlinearities in the battery's voltage response over its full operating range (dependent on the SoC level, Charging/discharging current rates, temperature etc.). This information can later be used by battery modeller to decide on the particular modelling methodology.

A12: Optimal sensor configuration for parameter estimation in single-phase hydrocarbon reservoirs

Edwin Insuasty*, **Paul Van den Hof***, **Jan-Dirk Jansen**** (Eindhoven University of Technology, The Netherlands*, Delft University of Techology, The Netherlands**)

Abstract: The selection of the sensor locations has a significant impact on the quality of estimated parameters in hydrocarbon reservoirs. They are distributed parameter systems modeled by partial differential equations, and in this context, the determination of the rock properties such as the porosity (ratio of the pore volume to the total volume) and permeability (a measure of the rock resistance to the fluid flow) is required based on limited number of sensors. In this work, we address the problem on where to locate the discrete measurements on single-phase hydrocarbon reservoirs such that the estimated parameters have minimal variance. For that, we have performed a low-dimensional parameterization of the large-scale parameter space of rock properties and have applied classical theory for experiment design and sensitivity analysis. We have derived the sensitivity equations with respect to the parameterization, and finally have found the measurement experiment that minimize the variance of the parameter estimates, which is optimal with respect a performance measure related to the Fisher information matrix.

A13: Identification and linearization of small loudspeakers

Ylva Jung, Martin Enqvist (Linköping University, Sweden)

Abstract: With the increasing number of mobile phones and tablets, where large loudspeakers are not desirable, there is an increased interest in improving

the sound from smaller loudspeakers. Since feedback of the output (in this case the sound) is not a possibility, open control is used, and a model of the system is needed. Based on Master's theses performed at Opalum (former Actiwave), we will present some ideas and open questions concerning the identification and control of loudspeakers, where the goal is to use a nonoptimal loudspeaker and improve the sound using signal processing.

Abstracts: Poster session B

Chair: Roger Larsson

B1: Some observations and questions on CRB for identification of stochastic Wiener systems

Bo Wahlberg (KTH Royal Institute of Technology, Sweden), **Lennart Ljung** (Linköping University, Sweden)

Abstract: We study the performance of maximum likelihood identification of stochastic Wiener dynamic systems. The main challenge is the stochastic process disturbance that propagates through the non-linear sensor. However, the corresponding ML cost-function and Fisher Information and Cramer-Rao Bound can in principle be determined by integration. Here, we would like to study how the properties of the non-linear sensor function affects the accuracy of the ML estimate. In order to obtain insights, we will study the problem of estimating a constant m_o that is affected by process noise v_t. The observations are $y_t = f(m_o + v_t) + e_t$, where $f()$ is a given non-linear function and e_t is measurement noise. We assume that the noise processes are independent white Gaussian with zero mean and given variances σ_v^2 and σ_e^2 . Even for this case it is non-trivial to obtain analytic insights how the function f and the noise variances affect the CRB of the ML estimate $\hat{m}$. The corresponding linearized problem reveals that variance $\hat{m}$ is proportional to $\sigma_e^2 + \sigma_v^2(f'(m_o)^2$. We study higher-order Taylor series expansions of $y_t = f(m_o + v_t) + e_t$ to obtain further results, and show that the non-linear sensor function f can actually improve the accuracy of $\hat{m}$.

B2: Hammerstein system identification: Avoiding linear block inversion problems in the presence of noise

Ricardo Castro-Garcia*, **Koen Tiels****, **Oscar Mauricio Agudelo***, **Johan A.K. Suykens*** (KU Leuven, Belgium*, Vrije Universiteit Brussel, Belgium**)

Abstract: In this work a methodology for identifying Hammerstein systems using a combination of Least Squares Support Vector Machines (LSSVM) and Best Linear Approximation (BLA) techniques is proposed. To do this, a novel method for estimating the intermediate variable is presented allowing a clear separation of the identification steps. First, an approximation to the linear block is obtained through the BLA of the system. Then an approximation to the intermediate variable is obtained using the inversion of the estimated linear block and the known output. Afterward a nonlinear model is estimated through LS-SVM using the estimated intermediate variable and the known input. Finally, a parametric re-estimation of the linear block is made. The obtained results demonstrate that also in the presence of noise, the method can effectively identify systems that follow the Hammerstein structure. The relevance of these findings lies in the fact that a very good estimation of the inner workings of a Hammerstein model can be achieved provided that enough input-output re-

alizations can be measured. These estimations include the nonlinear block, the intermediate variable and the linear block. Also, this work shows that through the use of regularization, the inversion of the estimated linear block is viable even in the presence of noise.

B3: Kinky inference for learning and controlling dynamical systems

Jan-Peter Calliess*, **Carl Rasmussen***, **Stephen Roberts**** (Cambridge University, UK*, Oxford University, UK**)

Abstract: We introduce kinky inference, an approach for performing inference over dynamical systems based on past state observations. The method can be construed as a nonparametric machine learning algorithm for which we can establish theoretical guarantees. We touch upon applications to nonlinear system identification and control. In particular, when kinky inference is utilised as the adaptive element of a nonparametric adaptive controller, we give simple illustrations of nonlinear systems where our inference guarantees can be converted to stability guarantees and bounds on the trajectories of a controlled plant.

B4: Weighting, regularization selection and transient in nuclear norm based identification

Mohamed Abdalmoaty, Håkan Hjalmarsson (KTH Royal Institute of Technology, Sweden)

Abstract: We consider a regularization method based on the re-weighted nuclear norm heuristic. We show using a numerical example that the re-weighting of the nuclear norm improves the estimate in terms of better fit. Second, we suggest an implementation method that helps in eliminating the regularization parameters from the problem by introducing a constant based on a validation criterion. Finally, we show how to deal with the effect of the transient when the initial conditions are unknown.

B5: The impact of smoothness on model class selection in nonlinear system identification: An application of derivatives in the RKHS

Yusuf Bhujwalla, Vincent Laurain, Marion Gilson (Université de Lorraine, France)

Abstract: In our poster, we examine the dependency between the kernel choice and the model class it represents. This is typically an undesired relationship, forcing the user to accept a trade-off between an acceptable variance characteristic and flexibility in the underlying function.

Hence, a method is proposed that explicitly constrains the smoothness of the model, by regularizing over the derivative of the function. This not only broadens the available model class, but also simplifies the selection of any hyperparameters.

We look at nonparametric models of nonlinear systems, and formulate the problem in the Reproducing Kernel Hilbert Space (RKHS). The proposed method is compared with an equivalent, established scheme by means of a simple example. It is shown that derivative-based regularization can help to extract useful structural information about an underlying system.

B6: A subalgebraic approximation algorithm for system identification of a discrete-time polynomial system

Jan H. van Schuppen (Delft University of Technology, The Netherlands)

Abstract: System identification of discrete-time polynomial systems without inputs is treated. Proposed is a subalgebraic approximation algorithm to estimate from a set of time series the parameters of the polynomial observer-representation of the system. A major step of the algorithm is to construct a subalgebra and a set of its generators for all polynomials from the past outputs to the future outputs. In the approximation, measures are taken to limit the complexity of the algorithm which include restrictions on the degrees of the polynomials and the Levinson recursion in the horizon of the past outputs. A detailed example wil be described based on computations with a computer program. Other examples are mentioned. Extensions to other classes of systems are described. The lecture is based on a long term research effort for rational systems and on scientific cooperation with: Jana Nemcova and Mihaly Petreczky.

B7: The Best Linear Approximation and linearisation

Adam Cooman*, **Ebrahim Louarroudi** ** **Yves Rolain***, **Gerd Vandersteen*** (Vrije Universiteit Brussel, Belgium*, Universiteit Antwerpen, Belgium**)

Abstract: Linearisation is omnipresent in the analysis of non-linear systems. On this poster, the link between two different linearisation techniques is explored: On the one hand, there is the Best Linear Approximation (BLA) which is can be considered as a linearisation of the large-signal behaviour of the system. On the other hand, we have the small-signal linearisation around a steady-state solution of the non-linear system. The BLA is used to model input-output behaviour of dynamic systems, while the second linearisation is often encountered in stability analysis.

A Combination both linearisation techniques is encountered in high-frequency measurements when the BLA is determined with an additional small-signal tickler excitation. The extra tickler signal allows to determine the BLA out-of-band or to estimate the BLA of systems with multiple inputs.

When combining the theoretical frameworks of the different techniques, some interesting analogies and assumptions were discovered, which will be detailed.

B8: Uncertainty in system identification: learning from the theory of risk

Patricio E. Valenzuela, Cristian R. Rojas and Håkan Hjalmarsson
(KTH Royal Institute of Technology, Sweden)

Abstract: This document addresses the issue of measuring uncertainty in optimization problems arising in system identification. The issue of uncertainty has been studied in the theory of risk, where the results are mainly employed in finance applications. Here we explore how the results in the literature of theory of risk can be used to obtain a systematic approach to uncertainty in system identification. For concreteness, the discussion is illustrated by an application to input design, but it can be extended to other areas of the field.

B9: Identifiability in dynamic network identification

Harm H.M. Weerts*, Arne G. Dankers, and Paul M.J. Van den Hof***
(Eindhoven University of Technology*, University of Calgary**)

Abstract: Dynamic networks are structured interconnections of dynamical systems driven by external excitation and disturbance signals. In [Weerts et al., 2015] we develop the notion of network identifiability, a property of a parameterized model set that ensures that module dynamics are uniquely related to the filters that specify the one-step-ahead predictors of all node signals in the network. It can be used to specify which presence of excitation signals will result in a unique representation of the network dynamics in a particular network model parametrization. This uniqueness is necessary for detecting the topology of the network from measured data, and for consistently estimating the network dynamics. We combine aspects of the classical notion of system identifiability with a uniqueness-oriented parametrization concept, and extend this to the situation of highly structured model sets. All node signals in the network are treated in a symmetric way. The presented concept and theory allow for the incorporation of particular structural prior knowledge of the network structure.

References:

H.H.M. Weerts, A.G. Dankers, and P.M.J. Van den Hof. Identifiability in dynamic network identification. In Proc. of the 17th IFAC Symposium on System Identification, 2015.

B10: Reflectometry-based electrical cable soft fault diagnosis

Qinghua Zhang (Inria, France), **Laurent Sommervogel** (WiN-MS)

Abstract: For the diagnosis of electrical cable failures, reflectometry-based methods analyze the reflected waves after the injection of an incident wave into the tested cable. Currently this technology is mainly applied to the detection of hard faults characterized by important impedance discontinuities, easily recognizable on the reflected waves. This poster is about the detection of soft faults, characterized by weak impedance variations, with no or slight impedance discontinuities. Classical reflectometry-based methods focusing on reflections from discontinuities become ineffective. The difficulties are that, on the one hand, the possible soft faults are of unknown shapes and at unknown positions, on the other hand, reflectometry measurements are made from a single end of the cable. The presented method is based on the telegrapher's equations, by computing the characteristic impedance distributed along the cable from reflectometry measurements made at one end of the tested cable. The developed hardware and software form a distributed impedance meter based on a single point measurement. The performance of this method is illustrated by experimental results.

B11: Recursive identification method for piecewise ARX models

Per Mattsson, Dave Zachariah, Petre Stoica (Uppsala University, Sweden)

Abstract: This poster deals with the identification of piecewise ARX models. By means of a sparse overparameterization, this is turned into a convex optimization problem, that can be solved by a recursive algoirthm. The proposed method is based on a covariance-matching methodology which adaptively penalizes model complexity. In this sparse estimation approach, tuning of user parameters is avoided, and the computational complexity is kept linear in the number of data samples. Numerical examples with both simulated and experimental data are used to validate the proposed method, and compare it to previously published methods.

B12: Calibration of inertial sensors using a dynamic model and maximum likelihood estimation

Fredrik Olsson*, Manon Kok, Kjartan Halvorsen*, Thomas B. Schön***
(Uppsala University, Sweden*, Linköping University, Sweden**)

Abstract: An inertial measurement unit (IMU) containing a triaxial inertial sensors (accelerometers and gyroscopes), can be used to give 3D position, velocity and orientation estimates. The accuracy of the estimates can be improved

significantly by properly calibrating the sensors to account for sensor errors. This work presents a calibration algorithm for the accelerometer and gyroscope, as an extension to the magnetometer calibration algorithm by Manon Kok et al. (2014). The algorithm works by rotating the IMU around its sensitive axes, without requiring the aid of a mechanical calibration platform or knowledge of the exact orientations of the IMU. The calibration problem is formulated as a maximum likelihood problem which combines a dynamic model, that uses the gyroscope measurements to describe the rotation of the IMU, with a measurement model for the accelerometer. So far the algorithm has been tested using Monte Carlo simulations and on experimental data collected from a Samsung Galaxy S5 smartphone, with promising results. Current challenges lie in the presence of outliers in the accelerometer measurements and observability issues when the rotation is limited.

Reference:
M. Kok and T. B. Schön, Maximum likelihood calibration of a magnetometer using inertial sensors. Proceedings of the 19th World Congress of the International Federation of Automatic Control (IFAC), pp. 92-97, Cape Town, South Africa, August 2014.

B13: Identification of complex mechatronic systems

Robert Voorhoeve, Tom Oomen (Eindhoven University of Technology, The Netherlands)

Abstract: Advanced control of mechatronic systems requires the identification of increasingly complex systems. This complexity typically lies in the high-order dynamics and the large input-output dimensions. The aim of this research is to develop fast, accurate, and reliable tools for frequency domain identification for such complex systems. A benchmark system is proposed to enable a thorough comparison of existing methods and facilitate the development of new reliable identification tools. New approaches for numerically reliable system identification are investigated, which involve data-dependent (bi-)orthonormal basis functions. Initial tests on the benchmark systems show promising results.

B14: Identification of piecewise affine state-space models via Expectation Maximization

Rafael Rui (Universidade Federal do Rio Grande do Sul, Brazil), **Tohid Ardeshiri** (Linköping University, Sweden)

Abstract: We focus on the identification of hybrid models, more precisely the identification of piecewise affine state-space models. Such models are used to approximate a nonlinear dynamical system by a model which switches between different submodels, where these submodels are linear state-space models. The proposed framework uses the Expectation Maximization (EM) algorithm

to identify the parameters of these submodels. In most of the current literature a discrete random variable with a discrete transition density is introduced to describe the transition between the different submodels, leading to further approximation of the dynamical system by a jump Markov model.

On the contrary, we use the cumulative distribution function (CDF) to compute the exact distribution of the predicted state given the last estimate of the previous state in a Bayesian setting. Gaussian mixture approximations are used to calculate the posterior distribution, where the Gaussian mixtures weights are calculated using the CDF of the continuous random variable given the measurements up to one step after each time instance and the latent variables estimate. The continuous latent state is estimated using the fixed-lag smoothing algorithm and the parameters are estimated using the maximum likelihood approach. The efficiency of the proposed method will be illustrated through the simulated model of the JAS 39 Gripen aircraft.

B15: Is it possible to solve complex problems with simple tools?

Roger Larsson, Martin Enqvist (Linköping University, Sweden)

Abstract: In order to make control law design effective one needs to make the most of the available system information. This is very true for the case of the control law design of a modern fighter aircraft. The flight characteristics of this kind of system varies from stable to unstable, from linear to nonlinear, and the flight control system needs to deal with all combinations of these. Also, the process noise characteristics for atmospheric flight is colored, which adds to the system identification complexity. The hypotheses under investigation is whether it is possible to perform system identification using a simple parameterized observer to get a stable predictor for this kind of a problem. The goal is to develop an easy-to-use engineering tool that requires a minimum of manual tuning. Such a tool should make it easier to obtain a high-accuracy aerodynamic model that can be used for the control law design.

Abstracts: Poster session C

Chair: Johan Dahlin

C1: Identification of inverse models for feedforward compensation: An optimal IV approach

Frank Boeren and Tom Oomen (Eindhoven University of Technology, The Netherlands)

Abstract: In this work, system identification of inverse models for feedforward compensation is investigated. It is shown that the estimation of the parameters of a feedforward controller can be reformulated as the estimation of an inverse model of a dynamical system in a closed-loop configuration. The aim of this poster is to enhance existing feedforward tuning methods by using closed-loop identification techniques. First, a pseudo-linear regression method based on instrumental variables is presented that leads to unbiased estimates with optimal accuracy for feedforward tuning. The proposed method exploits a bootstrap method to iteratively refine the instrumental variables. Second, preliminary results are presented to illustrate the value of iterations and stochastic approximation algorithms in inverse model identification. Finally, experimental results on a motion system are presented to compare the proposed approach to pre-existing methods.

C2: Nonparametric estimation of the frequency response matrix using local rational approximations

Dieter Verbeke, Johan Schoukens, Egon Geerardeyn (Vrije Universiteit Brussel, Belgium)

Abstract: The presented work concerns the estimation of non-parametric noise and frequency response matrix (FRM) models for multiple-input-multiple-output (MIMO) systems. Pintelon et al. (2010, 2011) established the local polynomial method (LPM) for dynamic multivariable systems. LPM results in a non-parametrical suppression of the noise and system transients in the frequency response matrix and noise-covariance estimates. The underlying principle is a local polynomial approximation of estimated transients, the measured spectra and/or transfer functions. McKelvey & Guérin (2012) acknowledged that transfer functions and transient terms can better be approximated by local rational functions with a common denominator polynomial. They suggest that this alternative approximation improves performance when the system shows strong resonant behaviour. The local rational method (LRM) of McKelvey & Guérin was only developed for single-input-single-output systems for arbitrary excitation signals in a specific noise framework. We want to extend the LRM to include MIMO systems, and the more general conditions (excitation signals, framework) in which the LPM is applicable. The development of these nonparametric estimation techniques is closely related to our overall research interest: identification of high-dimensional MIMO systems exhibiting lightly damped dynamics. Robust nonparametric estimation methods that are able to cope with

lightly damped systems play a key role in our strategy.

References:
R. Pintelon, J. Schoukens, G. Vandersteen, K. Barbé, "Estimation of nonparametric noise and FRF models for multivariable systems - Part I: Theory," Mechanical Systems and Signal Processing, vol. 24, no. 3, pp.573-595, 2010.
R. Pintelon, K. Barbé, G. Vandersteen, J. Schoukens, "Improved (non-) parametric identification of dynamic systems excited by periodic signals - the multivariate case," Mechanical Systems and Signal Processing, vol. 25, no. 8, pp.2892-2922, 2011.
T. McKelvey and G. Guérin. "Non-parametric frequency response estimation using a local rational model". Proceedings of the 16th IFAC Symposium on System Identification, July 11-13, Brussels, July 2012.

C3: Identification of polynomial Wiener systems via Volterra-Laguerre series

Daniel Jansson and Alexander Medvedev (Uppsala University, Sweden)

Abstract: A novel approach to the identification of discrete polynomial Wiener systems in absence of a priori information about the linear part is presented. To capture the system structure, the identification is performed via a Volterra series model whose kernels are parameterized in terms of Laguerre functions. A property of the resulting Volterra-Laguerre (VL) model enables a straightforward estimation of the output polynomial coefficients. It is shown that, under model structure mismatch, the identified VL model maintains the polynomial Wiener structure, but with biased estimates of both the linear and nonlinear block. Explicit expressions for the bias are derived and exploited in the design of an iterative bias reduction technique that yields improved estimates of the linear block as well as of the nonlinearity and also estimates the model error magnitude. The proposed approach is shown to outperform standard Wiener system identification methods in terms of both model fit and computational burden. Furthermore, the bias reduction algorithm is proven to uniformly converge for models with cubic output polynomials, but also demonstrated in numerical experiments to be effective for higher-order polynomials. Finally, the utility of the proposed method is demonstrated by applying it to human smooth pursuit system (SPS) characterization, where experimental eye-tracking data is used in the identification. The resulting models of the SPS provide better prediction accuracy than the previously studied ones.

C4: A class of nonconvex regularizations for mean filtering

Mohammadreza Malek-Mohammadi, Cristian R. Rojas, and Bo Wahlberg (KTH Royal Institute of Technology, Sweden)

Abstract: Recovering a piecewise constant signal from noisy measurements, known as mean filtering, has many applications in signal processing, economics,

finance, etc. A well-known approach to this goal is to solve a lasso-like optimization problem. The objective function in the associated optimization problem consists of a quadratic data fidelity measure as well as an ℓ_1 regularization term that induces sparsity of the first-order derivative of the recovered signal. However, this method, referred to as ℓ_1 mean filtering, in some cases, is unable to recover signal's change points where the true signal jumps to a new constant value. We propose a new class of objective functions where the ℓ_1 norm is replaced with a more-sparsity-inducing function. The proposed regularization is nonconvex; nevertheless, it is still possible to make the objective function convex. Accordingly, we find conditions under which the resulting optimization problem is convex.

To efficiently solve the resulting optimization problem, we propose an iterative method which involves solving a few weighted ℓ_1 mean filtering programs. By numerical optimization, we verify the superiority of our approach to ℓ_1 mean filtering.

C5: State-of-health estimation of lithium-ion battery using dynamical model derived from electric vehicles operating data

Giuseppe Giordano, Jonas Sjöberg (Chalmers University of Technology, Sweden)

Abstract: State-of-health (SOH) estimates of batteries are essential on-board electric vehicles (EVs) in order to provide safe, reliable, and cost-effective battery operation. Here, we present an approach for the estimation of the battery SOH indicator internal resistance. Battery models are constructed on the basis of ordinary EV operating data. The 10 s discharge resistance, which is an established battery figure-of-merit from laboratory testing, can be conveniently computed from the identified model parameters. Dynamical battery models based on a current input and a voltage output with model parameters dependent on temperature and state-of- charge are derived using AutoRegressive with eXogenous input (ARX) model structures. The suggested method is validated with usage data from emulated EV operation of an automotive lithium-ion battery cell. The resistance values are estimated accurately by the proposed model for a SOC and temperature range spanning typical EV operating conditions (average relative estimation error of 1.5 %). The method even provides an uncertainty interval for the resistance estimations, which is found to be very narrow. The linear identification of the model parameters and the resistance computation are very fast rendering the method suitable for on-board application and allowing to avoid laboratory tests for resistance estimation.

C6: Experiment design in oil reservoir water-flooding

M. Mohsin Siraj*, Paul Van den Hof*, Jan Dirk Jansen** (Eindhoven University of Technology, The Netherlands*, Delft University of Techology, The

Netherlands**)

Abstract: In the primary oil production phase of a petroleum reservoir, wells are drilled and the over-pressurized reservoir push the oil to the surface. Unfortunately, only 5–15% of the total amount of oil can be recovered this manner. In the secondary phase, to maintain a preferred production level, the application of an external force is required. Waterflooding is the most popular secondary recovery method in which water is injected from particular injection wells and the oil is produced through production wells [1]. Using a large-scale physics-based non-linear reservoir model with an economic objective function, the dynamic optimization of the water-flooding process has shown great improvement in the economic life-cycle performance of the oil reservoirs. One of the key challenges in such optimization is the uncertainty in the reservoir models which arises from the lack of information about the model parameters. Normally an ensemble Kalman filter is used to estimate both states and the parameters of the model. The purpose of this project is to explore the options of experiment design to increase the information contents in the output data. The experiment design is based on a linearized model around an operating point of the original non-linear model.

References:

[1] J.D.Jansen, S.G. Dourma, D.R Brouwer, P.M.J. Van den Hof, O.H. Bosgra and A.W. Heemink. Closed-loop reservoir management. Paper SPE 119098, 2009 SPE Reservoir Simulation Symposium, 24 February 2009, The Woodlands, Texas, USA.

C7: Model predictive oriented input design for closed-loop system identification: a graph-theory approach

Afrooz Ebadat, Patricio E. Valenzuela, Bo Wahlberg (KTH Royal Institute of Technology, Sweden)

Abstract: We present a new approach for Model Predictive Control (MPC) oriented experiment design for closed-loop systems. The method considers the design of an experiment by minimizing experimental cost, subject to probabilistic bounds on the input and output signals, and quality constraints on the identified model. The excitation is done by intentionally adding a disturbance to the loop. We then design the external excitation to achieve the minimum experimental effort while we are also taking care of the tracking performance of MPC. The stability of the closed-loop system is guaranteed by employing robust MPC during the experiment. The problem is then defined as an optimization problem.

In many industrial processes, the input and output signals are restricted to some specific sets due to physical limitations of actuators, which are also taken into account in the optimization problem as constraints. However, the aforementioned constraints result in non-convex problem. This problem is relaxed by assuming that the experiment is a realization of a stationary process with finite memory and finite alphabet and exploiting the results from graph theory.

The proposed technique is then evaluated through a numerical example

which shows that the proposed technique is an attractive alternative for closed-loop system identification.

C8: Nonlinear state-space identification of nonlinear systems exhibiting hysteresis dynamics

Alireza Fakhrizadeh Esfahani[*], **Jean-Philippe Noël**[**], **Gaetan Kerschen**[**], **Johan Schoukens**[*] (Vrije Universiteit Brussel, Belgium[*], University of Liège, Belgium[**])

Abstract: Hysteresis is a phenomenology commonly encountered in very diverse engineering and science disciplines. The defining property of a hysteretic system is the persistence of an input-output loop as the input frequency approaches zero. Hysteretic systems are inherently nonlinear, as the quasi-static existence of a loop requires an input-output phase shift different from 0 and 180 degrees, which are the only two options offered by linear theory. The identification of hysteresis is challenging, primarily because it is a dynamic kind of nonlinearity governed by internal, and so unmeasurable, variables. The present contribution aims at demonstrating the capability of nonlinear state-space models to accurately identify hysteretic behaviour. Nonlinear terms in the state-space model are constructed as a multivariate polynomial in the states, and their parameters are estimated by minimising a maximum likelihood cost function. Technical issues like the selection of the model order and the polynomial degree are discussed, and model validation is achieved in both broadband and sine conditions. The study is carried out numerically by exploiting synthetic data generated via the Bouc-Wen equations. The Bouc-Wen theoretical model consists in a first-order differential equation encoding the memory associated to hysteresis. This equation is coupled herein to a second-order differential equation representing a mechanical system with a single resonance. The coupled set of equations leads to a nonlinear dynamic system exhibiting rate-dependent hysteresis and hardening of its resonance frequency.

C9: Learning nonlinear system identification: From test case to an F-16 Fighting Falcon

Mark Vaes[*], **Yves Rolain**[*], **Johan Schoukens**[*], **Bart Peeters**[**], **Gaëtan Kerschen**[***], **Jean-Philippe Noël**[***] (Vrije Universiteit Brussel, Belgium[*], Siemens Industry Software[**], University of Liège, Belgium[***])

Abstract: Linear Time Invariant (LTI) methods are well established within the industry. However, when dealing with complex nonlinear systems like an F-16 Fighting Falcon, using these LTI methods might lead to a misinterpretation and/or bad results. To overcome this problem, a practitioner, who does not have any knowledge about nonlinear systems, should learn how to deal with them, not only in theory, but also in practice. This should allow the user to directly apply the methods on real complex nonlinear systems like the F-16 Fighting

Falcon.

To do this, a self-study kit is introduced that allows the user to learn nonlinear system identification at his/her own pace. This self-study kit contains two parts: a knowledge acquisition part and a small practical test case system, in this case a mechanical vibrating system, to perform hands-on exercises. The knowledge part focuses on giving the user intuition about nonlinear identification without going too deep into the theory. The hands-on exercises allow the user to assimilate this knowledge to obtain practical experience on the test system.

Even though the test system and the F-16 do not look alike at all, especially considering the size and the complexity of the system, their nonlinear behavior is similar. To show the similarity between the small mechanical test case system and the F-16 Fighting Falcon, the same FRF measurements on both systems are shown and compared. The test system proves indeed to be a good setup to learn nonlinear identification.

C10: Learning a stochastic model for skewed time series data with application on multivariate stochastic volatility estimation

Henri Nurminen*, **Tohid Ardeshiri****, **Robert Piché***, **Fredrik Gustafsson**** (Tampere University of Techology, Finland*, Linköping University, Sweden**)

Abstract: We present a novel adaptive filter for multivariate time series data with skewed measurement noise distribution. The filter is based on the multivariate skew normal distribution whose spread and skewness matrices are modeled as time-varying latent stochastic processes. The proposed filter estimates these matrices on-line using a variational Bayes approximation of the filter's posterior distribution. The time-update of the latent variables uses a forgetting factor parameter that describes the rate of variability in the latent processes.

The proposed filter is applied to stochastic volatility estimation of financial asset return data. Earlier studies have shown that the return distribution is time-varying and shows significant volatility clustering and skewness. The proposed filter captures these properties by describing the volatility with two slowly varying parameter matrices, spread and skewness. The proposed algorithm iterates Kalman filter type updates at each measurement instant, so it does not handle multimodality, but it can be computationally efficient compared to sampling-based methods when the state dimension is large.

C11: Recursive method of moments identification of Hidden Markov Models using convex optimization

Robert Mattila, Bo Wahlberg (KTH Royal Institute of Technology, Sweden), **Vikram Krishnamurthy** (University of British Columbia, Canada)

Abstract: Hidden Markov Models (HMMs) and associated Markov modulated time series are used widely for estimation and control in e.g. robotics, econometrics and bioinformatics. In our work, we modify and extend a recently proposed approach in the machine learning literature that uses the method of moments and a non-negative matrix factorization to estimate the parameters of an HMM. In general, the method boils down to a non-convex optimization problem. In our work, it is shown that if the observation probabilities of the HMM are known, then estimating the transition probabilities reduces to a convex optimization problem. A recursive algorithm is proposed for solving this problem, where we also employ a generalization of the Pythagorean identity to recast the problem into a non-constrained optimization problem. We also provide some ideas from current work-in-progress on how the observation matrix can be estimated, assuming the transition probabilities are known, using the method of moments. This problem is in general non-convex, so we employ convex relaxation techniques to make it approachable.

C12: On-line algorithms for Bayesian system identification

Diego Romeres, Giulia Prando, Gianluigi Pillonetto and Alessandro Chiuso (University of Padova, Italy)

Abstract: In this work we consider on-line system identification problems where model estimates are computed recursively as data become available. We shall compare different alternatives, including EM-type, first and second order methods, for updating the hyperparametrs. Connections between some of these updating rules will be drawn.

These alternatives will be compared in terms of accuracy as well as computational cost also via extensive Monte Carlo simulations.

C13: Decoupling noisy multivariate polynomials in nonlinear system identification

Gabriel Hollander, Philippe Dreesen, Mariya Ishteva, Johan Schoukens (Vrije Universiteit Brussel, Belgium)

Abstract: In the field of system identification, one special type of nonlinear models are the so-called block-oriented models, and more specifically the Wiener-Hammerstein models. When identifying parallel Wiener-Hammerstein systems, a multiple-input-multiple-output polynomial should be decoupled, that was obtained from noisy measurements. In this work, an earlier developed decoupling algorithm developed for the noiseless case is extended to the noisy case.

Let f be a multivariate polynomial function under the influence of noise, whose coefficients are approximated and let Σ_f denote the covariance matrix on these coefficients. We wish to decouple this function by finding transformation matrices V and W, such that f can be expressed as $f(u) = W \cdot g(V^T \cdot u)$, where the internal vector function g is a set of r univariate functions: every component g_i of g is only dependent on one variable x_i , which is the i-th component of the internal variable $x = V^T \cdot u$.

The earlier developed algorithm uses first-order derivative information of f and involves the so-called Canonical Polyadic Decomposition (CPD) of a tensor, which is, loosely spoken, a generalization of the singular value decomposition for two-dimensional matrices to multidimensional arrays of numbers. In this work, a weight matrix based on the covariance matrix Σ_f is added to the CPD. Three different weight matrices were tested: a diagonal weight matrix, block-diagonal weight matrix and a full weight matrix.

Results vary depending on the added noise. Also the full weight matrix, even though containing more information than the remaining weight matrices, is ill-conditioned, which may produce unexpected results in some cases.

C14: Quasi-Newton particle Metropolis-Hastings

Johan Dahlin (Linköping University, Sweden), **Fredrik Lindsten** (University of Cambridge, UK), and **Thomas B. Schön** (Uppsala University, Sweden)

Abstract: Particle Metropolis-Hastings enables Bayesian parameter inference in general nonlinear state space models. However, in many implementations a random walk proposal is used and this can result in poor mixing if not tuned correctly using tedious pilot runs. Therefore, we consider a new proposal inspired by quasi-Newton algorithms that may achieve better mixing with less tuning. An advantage compared to other Hessian based proposals, is that it only requires estimates of the gradient of the log-posterior. We provide numerical illustrations to investigate the properties of the new algorithm and compare its performance with some common alternatives.

Abstracts: Poster session D

Chair: Jonas Linder

D1: Filter interpretation of regularized impulse response modeling

Anna Marconato and Johan Schoukens (Vrije Universiteit Brussel, Belgium)

Abstract: In this work, we look at Bayesian regularization for FIR modeling from a different angle. 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, and we look more closely at how the parameters are penalized in the cost function. This approach allows one to embed prior knowledge directly in the regularization term, as a prefiltering of the model parameters. In this framework, new regularization structures can be designed, giving the user the freedom to adapt the problem formulation to his/her specifications.

D2: Nuclear norms for system identification – a direct input-output approach

Kristiaan Pelckmans, Ruben Cubo (Uppsala University, Sweden)

Abstract: This contribution studies a method for the identification of LTI systems based on the nuclear norm of the Hankel matrix of the model - termed NucID. The nuclear norm has been put forward as a convex proxy to a class of rank-constraints that are hard to work with. The rationale for investigating such approach is that the estimate is more flexible/robust in case of low Signal-to-Noise Ratios (SNRs), and other noisy effects in the data. This contribution explores the formalization, gives numerical results and brings up other issues for stimulating the discussion on the use of such approaches.

D3: Use of a semi-empirical electrochemical battery model to identify Li-ion battery degradation

Kotub Uddin*, Surak Perera, Dhammika Widanage***, and J. Marco***** (Ricardo-AEA, UK*, Maplesoft Europe Ltd., UK**, University of Warwick, UK***)

Abstract: Lithium ion batteries undergo complex electrochemical and mechanical degradation. This complexity is pronounced in applications such as electric vehicles where highly demanding cycles of operation and varying environmental conditions lead to non-trivial interactions of ageing stress factors. This work presents the framework for an ageing diagnostic tool based on identifying the physical parameters of a fundamental electrochemistry-based battery

model from non-invasive voltage/current cycling tests. Exploiting the embedded symbolic manipulation tool and global optimiser in Maple and MapleSim, computational cost is reduced, significantly facilitating rapid optimisation. The diagnostic tool is used to study the degradation of a 3.03Ah $LiC_6/LiNiCoAlO_2$ battery stored at 45°C at 50% State of Charge for 202 days; the results agree with expected battery degradation.

D4: Study on different numerical optimization strategies to compute the D-optimal input design for a simple Wiener system

Alexander De Cock*, **Kaushik Mahata**** **and Johan Schoukens*** (Vrije Universiteit Brussel, Belgium*; University of Newcastle, Australia**)

Abstract: For linear system the problem of optimal input design is considered to be solved. However, the extension to nonlinear system is not trivial and till now, only finite short memory system can be handled. Since a theoretical framework to describe the optimal input for nonlinear systems with infinite memory is still lacking, we follow a more pragmatic approach and resort to numerical optimization. In this work we evaluate different optimization strategies in order to compute the D-optimal Input Design for a simple Wiener system that consists of a linear second order system and third order polynomial nonlinearity. Special attention will go two distinct strategies. The first, referred to a Brute Force Optimization, directly optimizes the time samples of the input sequence. For the considered class of systems this approach results in a nonlinear and non-convex optimization, which is sensitive to the parameters settings of the optimization. The second strategy is called the Optimal Naïve Dictionary Design and constructs an input sequence that consists out of a concatenation of "elementary" designs from a predefined set of signals called the dictionary.

D5: On estimating initial conditions in unstructured models

Miguel Galrinho, Cristian R. Rojas and Håkan Hjalmarsson (KTH Royal Institute of Technology, Sweden)

Abstract: Estimation of structured models is an important problem in system identification. Some methods, as an intermediate step to obtain the model of interest, estimate the impulse response parameters of the system. This approach dates back to the beginning of subspace identification and is still used in recently proposed methods. A limitation of this procedure is that, when obtaining these parameters from a high-order unstructured model, the initial conditions of the system are typically unknown, which imposes that the measured output data be truncated for the estimation. For finite sample sizes, discarding part of the data limits the performance of the method. To deal with this issue, we propose an approach that uses all the available data, and estimates also the initial conditions

of the system. Then, we present an example of how this approach can be applied to a particular method, and use a simulation study to exemplify its potential.

D6: Bayesian identification of LPV Box-Jenkins models: A multidimensional kernel approach

Mohamed Darwish*, **Pepijn Cox ***, **Gianluigi Pillonetto****, **Roland Toth*** (Eindhoven University of Technology, The Netherlands*, University of Padova, Italy**)

Abstract: Many industrial control systems exhibit nonlinear behaviour, where linear modeling is becoming insufficient to support model based control design such that the increasing performance specifications can be fulfilled. However, Linear Parameter-Varying (LPV) systems offer a powerful framework to deal with such situations while preserving the linear relationship between the input and the output signals.

In this work, we introduce a nonparametric approach in a Bayesian setting to efficiently estimate, both in the stochastic and computational sense, Linear Parameter-Varying Box-Jenkins (LPV-BJ) models. The approach is based on the estimation of the one-step-ahead predictor model of general LPV-BJ structures, where the sub-predictors associated with the input and output signals are captured as asymptotically stable infinite impulse response models (IIR). These IIR sub-predictors are identified in a completely nonparametric sense, where not only the coefficients are estimated as functions, but the whole time evolution of the impulse response is estimated as a function. In this setting, the one-step-ahead predictor is modeled as a zero-mean Gaussian random field, where the covariance function is a multidimensional Gaussian kernel that encodes both the possible structural dependencies and the stability of the predictor. The unknown hyperparameters that parameterize the kernel are tuned using the empirical Bayes approach. The performance of the identification method is demonstrated on an LPV-BJ simulation example, by means of an extensive Monte Carlo study.

D7: Recursive identification of time-varying physical parameters for a mechatronic actuator

Arturo Padilla*, **Hugues Garnier***, **Juan Yuz**** (University of Lorraine, France*, Universidad Técnica Federico Santa María, Chile**)

Abstract: The physical properties of many mechatronic systems can vary with time due to temperature changes for instance. Such a case is addressed in this work, where the physical temperature-varying parameters for a mechatronic actuator are estimated. There are a few challenges to overcome, e.g. because the electric current acting on the actuator is not measured, or the fact that the identification has to be carried out from normal operational conditions. Other challenges are due to the complex friction effects acting on the actuator but

also to the closed-loop situation. This poster will present these challenges in more detail and will also describe some preliminary results based on the use of a recursive estimation procedure to directly estimate and track the physical parameter variations from the sampled measured data.

D8: Data driven predictive control based on model structures with orthonormal basis functions

Ahmad Alrianes Bachnas, Roland Tóth, Siep Weiland (Eindhoven University of Technology, The Netherlands)

Abstract: This work explore the concept of an adaptive model predictive control (MPC) scheme by integrating a flexible predictor model that utilizes orthonormal basis function (OBFs). The OBFs model structure offers a tradeoff of either adaptation of the expansion coefficient or the basis functions of the model. This adaptation can mitigate plant-model mismatch and can help to prolong the lifetime of the MPC. Moreover, since OBFs model structures can be seen as a generalization of FIR model structures, the incorporation of this scheme in FIR-based MPC is rather straightforward.

D9: Variance analysis of linear SIMO models with spatially correlated noise

Niklas Everitt, Giulio Bottegal, Cristian R. Rojas, Håkan Hjalmarsson (KTH Royal Institute of Technology, Sweden)

Abstract: Substantial improvements in the accuracy of identified linear time-invariant SIMO dynamical models are possible when the disturbances affecting the output measurements are spatially correlated. Not only the input spectra and noise correlation structure, but also the model structure of the modules, determine if there will be any improvement in accuracy at all. We illustrate how the variance-error of the parameter estimates for finite model orders depends on the noise correlation structure, model structure and signal spectra.

D10: Using convolution to estimate the score function for intractable state transition models

Liang Dai, Thomas Schön (Uppsala University, Sweden)

Abstract: This note revisits a result on the estimation of the score function, i.e. the gradient of the log-likelihood function, when the system has an intractable state transition kernel. We illustrate that such result can be found via the use of a basic property of the convolution operator.

D11: System identification applied for modelling of vortex-induced vibrations of circular cylinders

Jan Decuyper (Vrije Universiteit Brussel, Belgium)

Abstract: In this work we address the matter of modelling systems that are subjected to vortex-induced vibrations (VIV). Vortex-induced vibrations are fluid-structure interactions that are frequently found in the built environment, especially in marine applications. The vibrations are driven by fluctuating lift and drag forces resulting from vortex shedding patterns, typically seen in the wake of bluff bodies in fluid streams. The main novelty lies within the application of known identification techniques to the domain of fluid dynamics. Data of lift forces is generated using computational fluid dynamic simulations (CFD) of cylinders on which an oscillation is imposed. Challenging about modelling the dynamics of fluid-structure interactions is their inherent nonlinear behaviour. Using odd multi sine signals as an imposed oscillation of the cylinder (input) we are able to study the level of nonlinearity ascribed to the resulting lift force (output), acting on the cylinder. As a first approach the best linear approximation of the transfer function, relating the oscillation and the lift force, is constructed. In a later phase nonlinear state space identification will be applied to come to a true nonlinear model. Identification of systems subjected to VIV can help reduce the time expensive CFD simulations typically needed nowadays to predict the possibly harmful oscillating behaviour of structures.

D12: On identification via EM with latent disturbances and Lagrangian relaxation

Jack Umenberg*, Johan Wågberg, Ian R. Manchster*, Thomas B. Schön**** (University of Sydney, Australia*, Uppsala University, Sweden**)

Abstract: In the application of the Expectation Maximization (EM) algorithm to identification of dynamical systems, latent variables are typically taken as system states, for simplicity. In this work, we propose a different choice of latent variables, namely, system disturbances. Such a formulation is shown, under certain circumstances, to improve the fidelity of bounds on the likelihood, and circumvent difficulties related to intractable model transition densities. To access these benefits, we propose a Lagrangian relaxation of the challenging optimization problem that arises when formulating over latent disturbances, and fully develop the method for linear models.

D13: Graybox modeling of ships using indirect input measurements

Jonas Linder, Martin Enqvist (Linköping University, Sweden)

Abstract: A ship's roll dynamics is very sensitive to changes in the loading conditions and a worst-case scenario is the loss of stability. This work proposes

an approach for online estimation of a ship's mass and center of mass. Instead of focusing on a sensor-rich environment where all possible signals on a ship can be measured and a complete model of the ship can be estimated, a minimal approach is adopted. A model of the roll dynamics is derived from a well-established model in literature and it is assumed that only motion measurements from an inertial measurement unit together with measurements of the rudder angle are available. Furthermore, disturbance characteristics of the model are presented. Due to the properties of the model, the parameters are estimated with an iterative instrumental variable approach to mitigate the influence of the disturbances and it uses multiple datasets simultaneously to overcome identifiability issues. The proposed approach is validated using experimental data. The experiments were performed using a scale model of a ship in a wave basin in free run experiments. The experimental study shows that the properties can be estimated with quite good accuracy but that variance and robustness.