A proposed full-day pre-conference workshop on July 4 or 5, 2016,
to be held at the 2016 American Control Conference, Boston, MA

Identification of Linear, Parameter Varying, and Nonlinear Systems: Theory, Computation, and Applications

Instructors
Wallace E. Larimore; Adaptics, Inc, Email: larimore@adaptics.com
Pepijn B. Cox; Eindhoven University of Technology, E-mail: p.b.cox@tue.nl

Abstract

In this workshop, the powerful subspace identification method (SIM) is described for the well understood case of linear time-invariant (LTI) systems. Recent extensions are show for linear parameter-varying (LPV), Quasi-LPV, and general nonlinear (NL) systems such as polynomial systems. The presentation, following the extended tutorial paper (Larimore, ACC2013), includes detailed conceptual development of the theory and computational methods with references to the research literature for those interested. Numerous applications including aircraft wing flutter (LPV), chemical process control (LTI), automotive engine (Quasi-LPV, NL) modeling, Quanser 3 DOF gyroscope identification (Quasi-LPV, NL), and the Lorenz attractor (NL) are discussed. An emphasis is placed on conceptual understanding of the subspace identification method to allow effective application to system modeling, control, and fault diagnosis. In addition, an overview is provided on other LPV subspace identification approaches and iterative nonlinear optimization based identification schemes.

1. Background and Topics

Over the past decade, major advances have been made in system identification for the LTI cases of no feedback (Larimore, ACC1999) and unknown feedback (Larimore, 2004; Chiuso, TAC2010). Unfortunately, LPV and NL subspace identification approaches suffer heavily from the curse of dimensionality where computational complexity grows exponentially with linear increase in the number of inputs, outputs, or states and can result in ill-conditioned estimation problems with high parameter variances for real-world applications. In contrast, nonlinear optimization approaches based on the prediction error minimization (PEM) framework result in a heavy nonlinear optimization problem, prone to local minima and convergence problems.

The workshop presents a first principles statistical approach using the fundamental canonical variate analysis (CVA) method for subspace identification of linear time-invariant systems, with detailed extensions to linear parameter-varying and nonlinear systems. The LTI case includes basic concepts of reduced rank modeling of ill-conditioned data to obtain the most appropriate statistical model structure and order using optimal maximum likelihood methods. The fundamental statistical approach gives expressions of the multistep-ahead likelihood function for subspace identification of LTI systems. This leads to direct estimation of parameters using singular value decomposition type methods that avoid iterative nonlinear parameter optimization. This results in statistically optimal maximum likelihood parameter estimates and likelihood ratio tests of hypotheses. The parameter estimates have optimal Cramer-Rao lower bound accuracy, and the likelihood ratio hypothesis tests on model structure, model change, and process faults produce optimal decisions.

The LTI subspace methods are extended to LPV systems that are expressible in the LTI form where the constant LTI parameters are multiplied by parameter-varying scheduling functions depending on the system operating point. For example, this allows for the identification of constant underlying structural stiffness parameters while wing flutter dynamics vary with scheduling functions of speed and altitude operating point

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variables. This is further extended to Quasi-LPV systems where the scheduling functions may be functions of the inputs and/or outputs of the system (Larimore, Cox and Tóth, ACC2015). Quasi-LPV systems include bilinear and general polynomial systems that are universal approximators. The developed CVA subspace identification method for parameter-varying systems avoids the exponential growth in computation characteristic of many other SIM methods.

The workshop is continued with introducing alternative LPV subspace identification approaches, including novel basis reduced realization scheme on the impulse response (Cox, Tóth and Petreczky, LPVS2015), predictor based subspace approaches, and other alternatives. To improve the model estimate of SIMs in terms of the prediction error, it will be shown how this model estimate can be used as an efficient initialization for iterative nonlinear optimization techniques to overcome convergence problems and to decrease the computational load of the nonlinear optimization. The workshop will cover the two most popular nonlinear optimization techniques: the expectation-maximization method and the gradient-based optimization of the prediction error. Comparisons are made between system identification methods including subspace, prediction error, and maximum likelihood, for which CVA achieves considerably less computation time and higher accuracy.

2. Applications and Intended Audience

These new results greatly extend the possible applications of subspace ID to closed-loop linear, LPV and nonlinear systems for monitoring, fault detection, control design, and robust and adaptive control. The precise statistical theory gives tight bounds on the model accuracy that can be used in robust control analysis and design. Also precise distribution theory is available for tests of hypotheses on model structure, process changes and faults. Potential applications include system fault detection for control reconfiguration, autonomous system monitoring and learning control, and highly nonlinear processes in emerging fields such as bioinformatics and nano technology. Applications are discussed to monitoring and fault detection in closed-loop chemical processes, identification of vibrating structures under feedback, online adaptive control of aircraft wing flutter, identification of the chaotic Lorenz attractor, identification of the highly nonlinear Quanser 3 DOF gyroscope, and identification and monitoring of nonlinear automotive engines.

The intended audience includes practitioners who are primarily interested in applying system identification and monitoring techniques, engineers who desire an introduction to the concepts of system identification and maximum likelihood monitoring, and faculty members and graduate students who wish to pursue research into some of the more advanced topics.

3. Course Outline

LINEAR SUBSPACE SYSTEM IDENTIFICATION - Wallace E. Larimore

8:30-9:00 RANK OF A STOCHASTIC DYNAMIC SYSTEM
- Statistical Rank - Canonical Variate Analysis (CVA)
- Rank as Minimal State Order

9:00-9:30 SUBSPACE MAXIMUM LIKELIHOOD ESTIMATION
- Multistep Likelihood Function
- State Space Regression Equations

9:30-10:00 STATISTICAL MODEL ORDER/STRUCTURE SELECTION
- Kullback Information and Akaike Information
- Accuracy of Estimated Model

Break

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10:15-11:00 OPTIMAL IDENTIFICATION OF I/O AND CLOSED-LOOP SYSTEMS
- Remove Effect of Future Inputs on Outputs
- Model Nesting and Sufficient Statistics

11:00-11:30 PROCESS MONITORING USING CVA
- Low Rank Process Characterization by CVA
- Testing Hypotheses of Process Change

11:30-12:00 IDENTIFICATION AND CONTROL APPLICATIONS
- Tennessee Eastman Challenge Problem
- On-line Adaptive Control of Aircraft Wing Flutter

Lunch Break

CVA SUBSPACE ID OF LPV AND NONLINEAR SYSTEMS - Wallace E. Larimore

1:00-1:15 LPV SYSTEM IDENTIFICATION MODELS & METHODS
- LPV-ARX and LPV-SS Model Forms and Static Dependence
- Strict LTI System with Known Parameter Variation

1:15-1:45 CVA SUBSPACE ID OF LPV SYSTEMS
- ARX-LPV Model Fitting
- Remove Effects of Future Inputs on Outputs
- CVA Between Past and Corrected Future

1:45-2:30 LPV STATE & MODEL ESTIMATION
- AIC Selection of Model State Order
- LPV State Equations by Regression
- Multistep-ahead Likelihood Maximization
- Aircraft flutter – Optimal Control Over Operating Region

2:30-3:00 EXTENSION TO NONLINEAR POLYNOMIAL SYSTEMS
- Carleman Bilinear Representation of Polynomial Systems
- Equivalent Quasi-LPV Representation – Constant Coefficients

Break

ALTERNATIVE LPV-SS IDENTIFICATION METHODS – Pepijn B. Cox

3:15-4:00 ALTERNATIVES TO CVA SUBSPACE ID
- Concepts of Extended Observability, Reachability, and the Hankel matrix
- LPV Basis Reduced Ho-Kalman Realization
- PBSID, SSARX and Other Alternatives

4:00-4:45 ITERATIVE NONLINEAR OPTIMIZATION FOR SS IDENTIFICATION
- Expectation-Maximization Method to Maximize the One-Step-Ahead Likelihood
- Gradient-Based Optimization of the Prediction Error

APPLICATIONS – Pepijn B. Cox

4:45-5:30 NONLINEAR ID, CONTROL, AND FAILURE MONITORING APPLICATIONS
- Lorenz Attractor
- Quanser 3 DOF Gyroscope
- Identification & Failure Diagnosis of Automotive Engines
- Identification of NLPV Aerodynamic Models

4. Course Instructors

Wallace E. Larimore

Dr. Larimore received his Ph.D. and M.S. degrees in Statistics from George Washington University, and did his dissertation in the area of time series analysis. He has over thirty years experience in the development of statistical methods with applications to dynamical processes and time series data. He is founder and president of Adaptics Inc, and has developed the ADAPTx software for the automatic time series analysis and modeling of dynamical processes. Dr. Larimore has done fundamental work in extending the canonical variate analysis method to the analysis of time series data including the publication of the first paper on subspace system identification (ACC1983).

Dr. Larimore has applied these methods to financial and econometric data, modeling and control of vibrating structures, detection and modeling of brain waves, and modeling and control of chemical and industrial processes. He has more than 70 published papers, and has organized numerous sessions at professional meetings. He has given workshops on Automated Multivariable Time Series Analysis and System Identification at several dozen conferences of various professional societies as well as at a number of corporations. He is a member of the American Statistical Association, Institute of Electrical and Electronic Engineers, and the Society for Industrial and Applied Mathematics.

The 1994 Statistics in Chemistry Award given by the Chemometrics Committee of the American Statistical Association was awarded to Dr. Larimore of Adaptics, Inc, in collaboration with Professors Duncan A. Mellichamp and Dale E. Seborg and their former graduate students Dr. Charles Schaper and Dr. Andreas H. Kemna of the Department of Chemical and Nuclear Engineering, at the University of California at Santa Barbara. The award is for the outstanding collaboration between statisticians and chemists in an industrial setting as judged by innovation and impact on the field.

Pepijn B. Cox

Pepijn Cox was born in Arnhem, The Netherlands, in 1989. He has received his B.Sc. degree in Mechanical Engineering (cum laude) in 2010 and his M.Sc. degree in Systems and Control Engineering (cum laude) in 2013, both at the Delft University of Technology (TUDelft), The Netherlands. Currently, he is a Ph.D. student in the Control Systems group at Eindhoven University of Technology (TU/e), The Netherlands. Pepijn Cox's main research interest is in linear parameter-varying (LPV) and nonlinear system identification and modeling, which is done in collaboration with dr. R. Tóth and prof.dr. P.M.J. Van den Hof.

Pepijn Cox is in a research group which is more then 10 years active in the field of LPV system theory, identification, and control, which published on the topic of LPV identification one book; four book chapters; 10+ journal papers (to, among others, the Journal of Process Control, Automatica, and IEEE Transactions on Automatic Control); 40+ conference papers (to conferences such as Conference on Decision and Control, American Control Conference, IFAC Symposium on System Identification, European Control Conference).

5. Related Workshop Presentations

Dr. Larimore has given a number of one-day workshops as a part of conferences sponsored by professional societies on Automated Multivariable System Identification: Basic Principles with Control and Monitoring Applications with various co-presenters (Dale Seborg, Nancy Kirkendall, and Robert Kosut). These were given at the American Control Conference (1993-2004 except 1998), Conference on Decision and Control (1995), and ACC jointly with IFAC World Conference (1996). The attendance has varied from half a dozen to 45 attendees. The workshop was extended to include nonlinear systems beginning at ACC 2005, ACC 2006, ACC 2007, ACC2010, and ACC 2013(co-presenter M. Buchholz) and ACC2014. The ACC 2007 and

2010 had attendance in the high teens while ACC2014 had 9 attendees. ACC 2015 had 12 attendees, but ended after only 2 hours due to a medical emergency.

The proposed workshop contains substantial new material on new linear subspace methods for practical identification of LPV and nonlinear polynomial systems along with examples to illustrate the use and results of these methods. An invited paper discussing these new methods was first presented by Dr. Larimore at the 2012 IFAC Symposium on System Identification in Brussels, July 11-13, 2012. A 2-hour Tutorial Session was presented at ACC 2013 on Identification of Nonlinear Parameter-Varying Systems: Theory and Applications. Some of the material from the Tutorial Session papers including new theory and applications to Aerodynamic Flutter, Electric Vehicle Batteries, Automotive Engines, and the chaotic Lorenz attractor will be included in the workshop (see Sec. 6 References below of Tutorial papers presented at ACC2013). Also fundamentally new theory applicable to Quasi-LPV nonlinear (bilinear affine) systems developed in Larimore, Cox and Tóth as well as new results developed in Cox, Tóth and Petreczky will be presented.

6. References

M. Buchholz and W.E. Larimore, "Subspace Identification of an Aircraft Linear Parameter-Varying Flutter Model," Tutorial paper in *Proc. 2013 American Control Conference*, pp. 2263-2267, Washington, D.C., 2013

A. Chiuso, "On the Asymptotic Properties of Closed-Loop CCA-Type Subspace Algorithms: Equivalence Results and Role of the Future Horizon," *IEEE Trans. Automat. Contr.*, vol. 55, no. 3, pp. 634–649, 2010.

P.B. Cox, R. Tóth and M. Petreczky, "Estimation of LPV-SS Models with Static Dependency using Correlation Analysis", *Proc. 1st IFAC Workshop on Linear Parameter-Varying Systems*, pp. 91-96, Grenoble, France, 2015.

W.E. Larimore, "Identification of Nonlinear Parameter-Varying Systems via Canonical Variate Analysis," Extended tutorial paper in *Proc. 2013 American Control Conference*, pp. 2247-2262, Washington, D.C., 2013.

W.E. Larimore, "Large Sample Efficiency for ADAPTx Subspace System Identification with Unknown Feedback," in *IFAC Dynamics and Control of Process Systems*, pp. 293–298, 2004.

W.E. Larimore, "Automated Multivariable System Identification and Industrial Applications," in *Proceedings of the 1999 American Control Conference*, pp. 1148–1162, San Diego, CA, USA, 1999.

W.E. Larimore, "System Identification, Reduced-Order Filtering and Modeling Via Canonical Variate Analysis," in *Proceedings of the American Control Conference*, pp. 175–181, San Francisco, 1983.

W.E. Larimore and M. Buchholz, "ADAPT-Lpv Software for Identification of Nonlinear Parameter-Varying Systems," in *Proceedings of the 16th IFAC Symposium on System Identification*, pp. 1820 –1825, 2012.

W.E. Larimore and H. Javaherian, "Identification of Linear Parameter-Varying Engine Models," Tutorial paper in *Proc. 2013 American Control Conference*, pp. 2274-2279, Washington, D.C., 2013

W.E. Larimore, P.B. Cox and R. Tóth, "CVA Identification of Nonlinear Systems with LPV State-Space Models of Affine Dependence," in *Proc. 2015 American Control Conference*, pp. 831-837, Chicago, 2015.

J. Remmlinger, M. Buchholz, and K. Dietmayer, "Identification of a Bilinear and Parameter-varying Model for Lithium-ion Batteries by Subspace Methods," Tutorial paper in *Proc. 2013 American Control Conference*, pp. 2268-2273, Washington, D.C., 2013