

## **PhD projects in progress**

Fei Qi

### Bayesian Methods for Control Loop Diagnosis

The main objective of this study is to establish a diagnosis system for control loop diagnosis, synthesizing observations of different monitoring algorithms and a prior knowledge of the control loop, to suggest possible faulty sources based on Bayesian probabilistic framework. Some related open problems and issues will be investigated. An equally important objective of this study is to apply the proposed Bayesian diagnosis system to experimental and industrial processes to verify and demonstrate practicality and validity of the method.

Moshood Olanrewaju

### Advanced Filtering for Continuum and Noncontinuum States of Distillation Processes

The main objective of this proposal is to develop generalized observation strategies to estimate targeted features of distillation processes. In this study, distillation processes are used to generally refer to both conventional distillation and reactive distillation columns. The dynamic estimation methods for both continuum and noncontinuum states will be developed with the expectation to use them to address some outstanding process monitoring problems of distillation processes. Our contributions in this proposed work will be on three major areas, which are: improving the theoretical foundation of dynamic estimation methods for hybrid systems, experimental investigation of hybrid state estimation and computational algorithms development for industrial applications.

Xinguang Shao

### Soft Sensor Developments for Chemical Processes Using Bayesian Methods

The primary goal of this project is to develop a soft sensor for chemical process with cyclic loops using Bayesian methods. Both static and dynamic model will be considered. Although Bayesian network has been widely studied in recent years, it is evident from the available literatures that very little work has been done for the cyclic circumstances, and no Bayesian based soft sensor development has been reported for the chemical process with cyclic loops.

Hailei Jiang

### Detection and Diagnosis of Poor Control Performance

A typical process or power plant operates with hundreds if not thousands of control loops. For efficiency, all critical loops must operate at optimum levels. With such a large number of important loops, it is difficult for engineers to monitor and maintain these loops so that are operating under optimum conditions at all times. Therefore process and

performance monitoring systems are increasingly becoming necessary for early detection of abnormal operating conditions, or events/faults, safety violations and performance degradation before they lead to unexpected disruptions or even catastrophic failures. The monitoring of the performance of chemical processes has received much attention in the engineering research literature over the past few decades (Harris, 1989; Huang and Shah, 1999). A challenging task after detection of poor control performance is to diagnose and locate the root cause in order to rectify the situation. There are many reasons that can cause poor control performance, such as poor controller tuning, process nonlinearity, oscillatory disturbance and inaccurate process model for processes under model-based control, etc. How to effectively diagnosis these problems, such as what is the root cause of the oscillations in a plant, is an extremely important task for ensuring efficient and safe production. Unfortunately, the diagnosis of poor control performance has received little attention and remains an open research area (Qin, 1998). This thesis is concerned with developing new techniques for diagnosis of poor control performance. The main focus of this thesis is on the following two challenging topics in the area of performance diagnosis: (1) detection and diagnosis of plant-wide oscillations and (2) detection and diagnosis of model-plant mismatch. Several new methods and techniques are proposed to solve these two problems. The proposed methods are evaluated by application to pilot-scale and industrial processes to demonstrate the practicality and utility of this new class of performance monitoring and diagnosis systems.

### **Postdoctoral Fellow (PDF) projects in progress**

Dr. Kwanho Lee

Performance Analysis Toolbox and Solutions for industry

Dr. Shrikant Bhat

Process systems engineering approach for oil sands extraction process

Dr. Elom Domlan

Multi model approach for soft sensors and applications in oil sands industry

Dr. Fadi Ibrahim

Moving horizon estimation for chemical processes

### **PhD projects completed in 2007**

Fangwei Xu

Assessment of Control System Performance: The Effects of Disturbances

Over the last few decades, controller performance assessment has become one of the most active research areas in process control community. Though most algorithms are based on minimum variance control (MVC) benchmark, other methods, with consideration of time varying dynamics, disturbances, model plant mismatch etc., are gaining ground as more realistic benchmarks for advanced control monitoring. This thesis

focuses on the controller performance assessment under disturbance effects. Linear matrix inequalities (LMIs) and covariance analysis methods are used as main mathematical tools for solving problems.

First, the controller performance of a class of linear processes is investigated under linear time invariant (LTI) control subject to linear time varying (LTV) disturbances, abbreviated as the LTVD problem. The structured closed-loop response is introduced to formulate the performance limit problem and performance assessment problem. The problems are solved for both SISO and MIMO processes by using LMI techniques. The regular, weighted and generalized LTVD benchmarks are derived respectively with distinct objective functions which result in different control performance in dealing with different disturbances. A more general framework based on the structured closed-loop response is proposed for performance assessment subject to a pre-specified variance/covariance upper bound constraint. Its feasibility equivalence is derived with covariance control methods, giving rise to a full or reduced order solutions accordingly. An optional optimization strategy is presented for a practical solution by minimizing the gap between the resultant structured closed-loop response and the existing one in the sense of H1 norm. A higher level performance assessment for model predictive control (MPC) applications is studied with the consideration of disturbance effects. Both variability and constraint are taken into account for economic benefit potential. They are utilized as two tuning knobs to improve economic performance. The variance performance is shown to be readily transformed to the economic performance. A systematic approach is given to evaluate the performance of existing MPC applications, which includes variance and economic performance assessment, sensitivity analysis and tuning guidelines. Finally, a practical framework for industrial implementation is suggested. The software package developed in this thesis is plant-oriented with standard DCS interfaces and is readily applied to process industries.

Yutong Qi

### Dynamic Modeling of Solid Oxide Fuel Cell

In order to operate solid oxide fuel cell (SOFC) systems, it is necessary to investigate dynamic characteristics of SOFC through modeling and simulations. In this thesis, SOFC dynamics is presented in the form of non-linear state-space model (SSM). Performance and responses of SOFC are investigated through simulations. This thesis consists of four stages in solving the problems of interest. First we investigate how fuel enters the cell surface and produces electricity. Dynamics led by diffusion process and inherent impedance is investigated and modeled. Dynamic correlations between parameters in the primary flow and in the immediate vicinity of the triple phase boundary (tpb) are considered in the form of transfer function as well as ordinary differential equation (ODE). A new equivalent circuit that can emulate both internal and external dynamic characteristics of SOFC is proposed to represent the effect of inherent resistance and double layer capacitance. Through simulations, a phenomenon of slow response of voltage in current interrupt experiment is explained. In the second stage, we consider transport processes from the cell surroundings to a finite volume of tubular SOFC composite, such as internal reforming/shifting reaction, fluid transport, and heat transfer. Combined with dynamics developed from the first stage, a detailed SSM with 28 states is

developed. Mole fractions, temperatures, flow velocities etc. are investigated and dynamically modeled through mass/energy/momentum balance. Dynamic responses of each physical variable to step changes of inlet variables as well as load changes are investigated through simulations. In the third stage, the dynamic model for the finite volume of tubular SOFC is expanded to a one-dimensional (1-D) dynamic model, in the form of non-linear SSM. With known total current demand, the dynamic current density distribution is developed by solving the equivalent circuit. Non-flowing solid phase variables are dynamically modeled. Dynamics of the flowing phase variables and their distributions are developed in the form of partial differential equations (PDEs). Aiming to solve the distributed parameter problem approximately, an innovative analytical solution for a 1-D reacting gas flow problem is developed. The solution is applied to the 1-D dynamic model of SOFC. The developed model can reduce computations while maintain reasonable precision. The explicit solution makes the 1-D dynamic model more applicable for further control studies. Dynamic performance and parameter distributions of SOFC are investigated through simulations. Finally, with the aim for simpler control application, an 2nd order nonlinear lumped parameter SSM is built. Input-output parameters of the SOFC stack are analyzed. Faster processes are approximated by their steady state solutions. Solid phase temperatures are modeled by dynamic equations owing to their slow response and dominant role played in SOFC dynamic responses. Simulations show that the lumped model can reasonably approximate dynamics of the SOFC shown by the detailed model.

AKM Monjur Murshed

#### Modeling, Control and Fault Detection of Solid Oxide Fuel Cell System

System modeling, controller design and process monitoring are three integral parts of the advanced process control strategies, which are intricately dependent on each other. From the view point of process control, the models should be easy to use for designing controller and yet be detailed enough for giving a true account of the system dynamics. In this work, two types of models, named lumped and detailed, have been developed for a planar solid oxide fuel cell. The models take electrochemical and thermal aspects into account and provide a set of first-order nonlinear ordinary differential equations. In the lumped model, a uniform temperature throughout fuel cell is assumed whereas in the detailed model uniform temperature distribution is assumed only within each components of the fuel cell. Zero-dimensional thermal models of fuel cell system component such as heat exchangers, reformer and burner are also provided for fuel cell system simulation. The advantage of using capacitor in parallel to the fuel cell is discussed along with the necessary formulation of the equations.

With the advent of cheap computational power, a surge of application of previously non-implementable complex controllers such as nonlinear model predictive controller (NMPC) has been seen in the industries. In this work, NMPC has been applied on the fuel cell system to compare its performance with various linear and nonlinear controllers. There are numerous fault detection and isolation techniques in the academics works. Of them, principal component analysis (PCA) is widely used for fault detection of linear, steady-state systems. The disadvantage of PCA is that it can not incorporate process knowledge.

Thus, an algorithm for hybrid PCA is provided which can take constraints into consideration by presenting PCA as a linear matrix inequality.

Xiaorui Wang

Multirate Predictive Control and Performance Assessment

The objectives of this thesis are to develop data-driven approaches for control performance assessment and predictive control design for multirate systems. Some related outstanding problems for univariate systems are also addressed. The benchmark is chosen as minimum variance control (MVC) to assess multirate control loop performance because MVC provides us a theoretical lower bound of the output variance under linear feedback control, and it provides useful information such as how well the current controller is performing and how much "potential" there is to improve the control performance. Generally speaking, a multirate controller performs better than a slow-single rate (SSR) controller but worse than a fast single-rate (FSR) controller in the sense of minimum variance control. This conjecture is theoretically proved in Chapter 2 for a continuous linear time-invariant (LTI) single-input and single-output (SISO) system. The optimal FSR multirate and SSR controllers are designed under the same performance criterion: variance of the fast sampled output. Basic statistical properties of the discretization of continuous stochastic disturbance models are investigated. A linear matrix inequality (LMI) approach is developed to derive the optimal controllers for dual-rate (DR) and SSR loops. Chapter 3 discusses data-driven MVC design and control performance assessment based on the MVC-benchmark for multirate systems. A lifted model is used to analyze the multirate system in a state-space framework and the lifting technique is applied to derive a subspace equation for multirate systems. From the subspace equation the multirate MVC law and the algorithm to estimate the multirate MVC-benchmark variance or performance index are developed. The multirate optimal controller is derived from a set of input-output open-loop experimental data and thus this approach is data-driven since it does not involve an explicit model.

The presented MVC-benchmark algorithm requires a set of open-loop experimental data and closed-loop routine operating data. In contrast to traditional control performance assessment algorithms, no explicit models or model parameters, namely, transfer function matrices, Markov parameters or interactor matrices, are needed in the data driven approach. Besides the data-driven MVC control, predictive control laws are also designed in Chapter 3 and 4 for both single-rate and multirate systems via system open-loop input-output data. Comparing with the previous data-driven predictive control approach, the developed predictive controllers can handle systems where only partial on-line outputs measurements are available and multirate systems. This is to circumvent the problems that in reality, some outputs may not be measured in real-time, or are too costly to measure at fast sampling rate.

Jiandong Wang

Cyclo-Stationary Signal Analysis & Applications in System Identification

System identification deals with the problem of building mathematical models of dynamical systems based on the observed data. Most contemporary studies in this field

have a fundamental assumption: the observed data are stationary, which means that statistical characteristics of the data do not change with time. The thesis is motivated by an “ambitious” thought: is it possible to remove or weaken this assumption so that the knowledge in the field can be advanced? The answer is positive by introducing cyclo-stationary signals, which exhibit periodicity in their mean, correlation, and spectral descriptions. The thesis consists of two parts. The first part studies cyclo-stationary signal analysis, including cyclo-period estimation, cyclo-statistic estimation and cyclo-spectral theory; they provide the second part with powerful computational tools and build up a solid theoretical background. The second part is to exploit cyclo-stationarity in system identification, including finite-impulse-response modeling for errors-in-variables/closed-loop systems, and blind identification of Hammerstein nonlinear systems. The main contributions achieved are briefly described as follows:

1. Cyclo-period estimation: A new method, named as the variability method, is proposed to estimate the cyclo-period of a discrete-time cyclo-stationary signal. Properties of the variability method are analyzed and compared with three existing cyclo-period estimation methods via simulation and real-life examples.
2. Cyclo-statistic estimation: We summarize the existing estimators of the time-varying mean/correlation and cyclic correlation/spectrum, and supplement a new cyclic spectrum estimator: the blocking-based estimator, and discuss implementation issues of these estimators.
3. Cyclo-spectral theory: Two problems in the spectral theory of discrete-time cyclostationary signals are studied: (i) four types of the cyclo-spectrum representation are presented and their interrelationships are explored; (ii) the problem of the cyclo-spectrum transformation is attacked in the framework of multirate systems using the blocking technique as a systematic solution.
4. Finite-impulse-response modeling for errors-in-variables/closed-loop systems: A complete study of the cyclic correlation analysis, which consistently estimates finite impulse response models, is developed including the time- and frequency-domain statistical performance of the models.
5. Blind identification of Hammerstein nonlinear systems: A new blind approach is proposed for identification of Hammerstein nonlinear systems by exploiting input’s piecewise constant property. In a real-time laboratory experiment, the proposed approach is successfully applied to identify a Hammerstein model for magnetorheological dampers.

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