Research Abstracts 1998 - PhD Projects in Automatic Control

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Research Abstracts 1998

PhD Projects in Automatic Control

Department of Automatic Control
Lund Institute of Technology

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Title and subtitle

Research Abstracts 1998 – PhD Proejcts in Automatic Control

Abstract

This report consists of short summaries of the research done by PhD students at the Department of Automatic Control at Lund Institute of Technology.

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Contents

Modeling with Quantified Accuracy

Lennart Andersson

Keywords: Model simplification, Model comparison, Uncertain models, Nonlinear models, Integral quadratic constraints, Linear matrix inequalities, Error bounds
Supervisors: Anders Rantzer
Start of project: 1993-10-01
Course Points: 75
Publications: 1 lic thesis, 2 submitted journal papers, 5 conference papers
Plans: PhD during 1999

State of the art

Today there are a lot of available methods to obtain simplified models with associated error bounds, in particular for standard linear time-invariant models. However, for more complex models such as models with uncertainty and nonlinearities there still remains a lot to be done.

Goal

The purpose of this project is to consider simplification of complex models.

Goals achieved:

- Error bounds for uncertain and nonlinear models
- Frequency dependent error bounds for uncertain linear models

Goals to achieve:

- Robustness of equilibria in nonlinear systems
- Application example in power systems
- Survey of existing simplification methods in control

Research Approach

We use integral quadratic constraints and linear matrix inequalities to obtain results for simplification of models.

Milestones

summer 98	Robustness of equilibria in nonlinear systems
fall 98	Application example in power systems
spring 99	Writing thesis

Results

My first work at the department was together with Anders Hansson on Extreme value control. An optimal control problem was solved numerically using the Bellman equation. This resulted in my master thesis, Andersson (1993), and the conference papers Andersson and Hansson (1994a); Andersson and Hansson (1994b). Then for over a year I was only taking courses and teaching.

In the spring 1995 I started doing research together with Anders Rantzer. We considered simplification of nonlinear and uncertain models using integral quadratic constraints. To learn more about existing results I visited Caltech for three month, where I worked with Carolyn Beck. This work resulted in the conference papers Andersson and Beck (1996a); Andersson and Beck (1996b). A journal article, Andersson *et al.* (1996), together with both Beck and Rantzer was also written.

During the summer 1996 Rantzer and I considered the special case with linear and time-invariant uncertainties. The result of this work is the conference paper Andersson and Rantzer (1997a) and a journal article Andersson and Rantzer (1997b).

During fall 1996 I sorted out some details and wrote my licentiate theses, Andersson (1997), which I presented in January 1997. Since then I have been working on some different problems; simplification of models with nonlinearities, simplification of power system and robustness of equilibria in nonlinear systems.

External Contacts

During my visit to Caltech, the fall 1995, I did some work together with Carolyn Beck. This work was continued during the spring 1996, while Carolyn did a postdoc in Lund.

External contacts working with power systems are Magnus Akke at Sydkraft and Olof Samuelsson at IEA.

Course work

At the end of the spring term I will have at least 75 points. By taking the Synthesis course this fall, I will reach the 80 points required.

Service to the Department

I have been involved in arranging the Lund-Lyngby day on control during the fall 1996 and spring 1997. I supervised the thesis Ahnelöv (1995) and assisted in the supervision of the thesis Lantz (1997). The main service to the department has been as a teaching assistant in the following courses:

Adaptive Control (1)	Process Control (1)
Identification (2)	Basic Course FED (2)
Computer Controlled Systems (1)	Basic Course M (1)
Nonlinear Control and Servo Systems (2)	

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ANDERSSON, L. and C. BECK (1996b): "Simplification methods for uncertain models." In *Reglermöte 96*, pp. 49–50. Luleå, Sweden.

ANDERSSON, L. and A. HANSSON (1994a): "Extreme value control of a double integrator." In *Proc. 33rd IEEE Conference on Decision and Control.* Orlando, Florida.

ANDERSSON, L. and A. HANSSON (1994b): "Olinjär extremvärdesreglering – ett exempel." In *Reglermöte 94.* Västerås, Sweden.

ANDERSSON, L. and A. RANTZER (1997a): "Frequency dependent error bounds for uncertain linear models." In *Proceedings of the American Control Conference.* Albuquerque, New Mexico.

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ANDERSSON, L., A. RANTZER, and C. BECK (1996): "Model comparison and simplification." Submitted to the International Journal on Robust and Nonlinear Control.

LANTZ, M. (1997): "Robustness analysis using Omola with application to power networks." Master thesis ISRN LUTFD2/TFRT--5585--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Integrated Control and Scheduling

Anton Cervin

Start of project: 980501

Supervisor: Karl-Erik Årzén

Keywords: Real-Time Systems, Scheduling Theory

Course points: 0 (980831).

State of the art

In the design of real-time control systems, there has been separation between the design of controllers and their actual implementation as tasks in a CPU. The sampled-data control theory is based on fixed sampling periods. On the implementation side, there exists scheduling theory (e.g. rate-monotonic analysis) for periodic control tasks with fixed sampling intervals and known worst-time execution times. The theory does not support variable sampling intervals or execution times, which occur in many control applications.

Goal

The goal is to develop dynamic control and scheduling techniques and theories, in order to obtain better control performance and better CPU utilization.

Research Approach

An early effort would be to investigate possibilities of introducing some dynamics into existing scheduling theory. Since good control performance is the ultimate goal, suitable measures of performance should be looked into. Case studies could be supplied by the research group's industrial nodes.

Milestones

- 9812: State of the art survey of integrated control and scheduling.
- 0006: Licentiate thesis

- 0303: PhD thesis

External Contacts

During May–July 1998, I spent two months at the Software Engineering Institute, Carnegie Mellon University, working with the project's external contact Lui Sha. Since then, Lui Sha has become a full professor at the University of Illinois.

Course Work

As of August 31, 1998 I have 0 course points, not counting 16 extra undergraduate points. This fall I plan to take the courses Synthesis (given by the department), Design of Software for Embedded Real-Time Systems (an ARTES graduate course given by Martin Törngren, KTH), and Optimization (given by the Department of Mathematics). As for the spring of 1999, there are several possibilities, among them the control courses Linear Systems, Nonlinear Control and Servo Systems, and System Identification.

Service to the Department

During the fall of 1998, I will be teaching assistant in Real-Time Systems and laboratory assistant in Automatic Control, Basic Course.

Modelling, Validation and Validity Control

Jonas Eborn

Keywords: Computer aided engineering, modelling, object-oriented modelling, power plant, process models, model validation, parameter estimation.
Supervisors: K. J. Åström, S. E. Mattsson
Start of project: 950101
Course Points: 50 (980101)
Publications: 1 paper, 7 conference papers (980501)
Plans: Millenium PhD

State of the art

The **K2** model database, developed for thermal power processes, has been used to model a number of process applications. A model of the water-steam cycle of Värnamo bio-gas power plant has been built, but lacks a correct parameter set and validation against measured data.
Parameter optimization with IDKIT and OMSIM has been used for structural validation of the Åström-Bell drum boiler model with good results.

Goal

Develop a validated thermo-hydraulic model library with built-in automatic validity control during simulation. Find a model validation approach (*methodology*) that is useful for physical models.

Research Approach

The thermo-hydraulic library is developed from first principles. The advanced language concepts in Modelica™ will be used to make the library general and adaptable to different model complexities. Also, the *class parameterization* concept will be investigated for flexible parameterization of unit models.
Model validation through parameter optimization could be used to give validity regions for models. This will be investigated through case studies with measured process data.

Milestones

Develop a general thermo-hydraulic base library in Modelica™ together with Hubertus. This should be finished and tested on smaller examples in September-October. Use *TheH*-library to build a model of Värnamo power plant and validate the model and the library against measurements from field tests in Värnamo. This should be finished late in the spring '99.

Results

My licentiate thesis [4] described the structure and use of the **K2** model library for thermal power plants. Four papers were contained in the thesis, [7, 11, 6, 8].

External Contacts

Sydkraft Konsult AB: Jan Tuszynski, Jörgen Svensson, Björn Nilsson.
Alfa Laval Thermal AB: Stefan Burg, Rolf Ekelund.
Electricité de France: Damien Faille, Pascale Bendotti.

There are no visits abroad planned.

Course Work

Before the licentiate thesis I completed 50 points courses. During the spring term I will take 8 points and have another 10 points of course projects that should be completed this year.

Service to the Department

System Identification: -98, -97.
Automatic Control(EFD): -97, -96, -95.
Automatic Control(M): -95.
Process Control: -96.
Always responsible for seminar announcements: 95-99?

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[16] H. TUMMESCHEIT and J. EBORN. "Developing a thermo-hydraulic base library in Modelica." In *Reglermöte'98 Preprints*, Lund, Sweden, 1998.

Real-time Control Systems

Johan Eker

Keywords: Real-time, Scheduling, Programming languages.
Supervisors: K. J. Åström, K. Årzén.
Start of project: 950101
Course Points: 45
Publications: 1 Lic. thesis, 3 conference papers
Plans: Dr HT1999

State of the art

Embedded control systems are today created using tools that give insufficient support for rapid prototyping and code reuse. New tools for implementation of embedded controllers are necessary. This paper presents a software framework for implementation of embedded control systems. The PAL language is presented. PAL is designed to support implementation of control algorithms in particular. A run-time system called Pålsjö is also introduced. Algorithms written in PAL may be executed in the Pålsjö system. The Pålsjö system is designed to allow on-line system configuration and reconfiguration. There are several widely used prototyping systems today. One is Autocode from Integrated Systems, another is Real-time Workshop from MathWorks.

Goal

We are currently working on the next generation of PÅLSJÖ framework. We aim at constructing a much more flexible environment with better support for hybrid controllers and more intergration when it comes to real-time scheduling and controller design. There are a number of important issues that were taken into account when the PÅLSJÖ framework was designed. The main goal was to create a *rapid prototyping* environment. In order to achieve this the system must have good support for *code reuse and algorithms libraries.* Furtermore, the framework should be *expandable*, in the sense that it should be fairly easy to add new feature and components. The system should be used as a test bench for new algorithms so all controllers should be *configured on-line.* Finally and an application built using the framework should not differ from an application built from scratch in code size or execution speed.

Research Approach

Try to define problems at the borderline between control theory and real-time computing. Create a test bed for experiments with new controller structures,

Results

A software framework for dynamically configurable controllers.

External Contacts

Lui Sha at Software Engineering Institute, Carnegie Mellon University, Per Påhlsson at Diana Control, and Jörgen Malmborg at Space Systems Sweden.

Service to the Department

AK(2), Real-time(3)

References

EKER, J. (1997): *A Framework for Dynamically Configurable Embedded Controllers.* Lic Tech thesis ISRN LUTFD2/TFRT--3218--SE, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

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MALMBORG, J. and J. EKER (1997): "Hybrid control of a double tank system." In *IEEE Conference on Control Applications.* Hartford, Connecticut.

Motion Control of Open Containers with Slosh Constraints

Mattias Grundelius

Keywords: Optimal Control, Motion Control, Liquid Slosh.
Supervisors: B. Bernhardsson, K. J. Åström, T. Hägglund.
Start of project: 961001
Course Points: 44 (980601)
Publications: 3 conference papers (980601)
Plans: Lic september 98, Dr HT2000

State of the art

The structure of the acceleration profile is determined and then the parameters are tuned using experiments and the experience of the development engineers.

Goal

Develop methods for calculation of acceleration profiles.

Research Approach

Derive a model that describes the sloshing phenomena. Apply optimal control techniques to calculate the acceleration profile.

Milestones

- Slosh measurement
- Slosh model
- Calculation of optimal trajectories
- Evaluation of control performance
- Derivation of more accurate nonlinear slosh model

Results

Equipment that can measure the surface elevation has been acquired. A simple slosh model has been derived. Both minimum-time and minimum-energy acceleration profiles have been calculated. The various acceleration profiles have been evaluated on the experimental setup with good results. Comparison with the acceleration profiles used in practice has also been done showing the advantage of the calculated acceleration profiles.

External Contacts

Close collaboration with Tetra Pak Research & Development AB in Lund. The contact consists of regular project meetings (4 times/year). They have also supplied us with the experimental equipment.

Course Work

Now I have 44 points and at the end of the spring semester 1998 I aim to have 54 points.

Service to the Department

Laboratory development in the courses Real-time systems and Process Control. Taught Real-time systems (2 times) and AKM (2 times).

References

GRUNDELIUS, M. and D. ANGELI (1996): "Adaptive control of systems with backlash acting on the input." In *Proceedings of the 35th IEEE Conference on Decision and Control*. Kobe, Japan.

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ÅKESSON, M., M. GRUNDELIUS, and M. JOHANSSON (1996): "New software for the control education in lund." In *Utbildningsdagen Reglermöte'96*. Luleå, Sweden.

Friction in Control Systems — Project Status Report August 1998

Magnus Gäfvert

Keywords: friction modelling, dynamic friction models, friction compensation.
Supervisor: K. J. Åström
Start of project: 961001
Course Points: 76
Publications: 3 journal papers, 3 conference papers
Plans: Lic. Fall 1998, Ph.D. Spring 2000

State of the art

Friction modelling with dynamic friction models is an area subject to strong attention from both industry and the academic community. Apart from intellectual curiosity this is driven by strong engineering needs in a wide range of application. Friction is a higly nonlinear phenomenon that deteriorates performance in many applications, hence posing great challenges to control engineers. It is necessary to have good models of friction phenomena to understand friction behavior and to be able to compensate for it. The common way to model friction is to use simple static memoryless relay type models. Lately the interest in more complex dynamic models has increased due to emerging demands in performance. There is a number of dynamic phenomenological models originating from a model presented by Dahl in the 60s. Two recent models are the LuGre model presented by Canudas de Wit and Lischinsky in Grenoble and Olsson and Åström in Lund in 1995, and a model presented by the french researchers Bliman and Sorine in 1996. The LuGre model has resulted in two PhD disserations and several conference and journal papers. It has proven to be useful in many applications. The publications regarding the Bliman-Sorine model is less oriented towards applications, but rather explores mathematical properties in depth.

Goal

The goals with my current research task are reached at this time. My near term plan is to put my results together in a licenciate thesis. After that I will change to another research subject.

The first goal of my research was to explore the relations between the LuGre and the Bliman-Sorine models. It is of interest to know in which ways the models differ, and which model is more suitable for a certain application.

The second goal was to further explore the properties and applicability of the LuGre model.

The third goal was to implement a number of friction compensation algorithms based on different friction models on a real process, and to experimentally compare the properties of the algorithms.

Results

Comparisons between the LuGre and the Bliman-Sorine models revealed damping problems with the Bliman-Sorine model. Problems with trajectory dependent behavior with the model was also discovered. Limit cycling properties with the models were also investigated, and compared with experiments. Describing function analysis with the models were performed, which gave some useful insight. The results were presented in the conference paper Gäfvert (1997). Some of the results were further developed, and were also published in the survey journal paper Olsson *et al.* (1998).

A new application of the LuGre model in robot control was presented in the conference paper Panteley *et al.* (1997). A passivity based adaptive controller with integrated friction compensation ensures global position tracking to an n-dof robot manipulator. A simulation study was included in the paper. The controller was also presented in the journal paper Panteley *et al.* (1998), together with a comparison with another well known adaptive friction compensator.

The Furuta pendulum has been used as an evaluation platform for friction compensation. Some different compensation strategies has been implemented and tested experimentally. Modifications of previous analysis of LuGre observer based compensation has been done in order to handle the more complex dynamics of the Furuta pendulum. The results are presented in the internal report Gäfvert (1998) and submitted in the conference paper Gäfvert (1999).

External Contacts

The project has been driven in extensive cooperation with Canudas de Wit's research team at Laboratoire d'Automatique de Grenoble, France, and with Romeo Ortega at SUPELEC, Paris, France, according to the references below. Visits and discussions with researchers at the Department of Machine Design, Royal Institute of Technology, Sweden, has provided insight and inspiration. Informal contacts with some industry representatives, e.g. at Alfa Laval Agro, has spread some of the results outside the academic sphere.

Course Work

As of the 10th of August 1998 I have 76 points and at the end of the fall semester I aim to have 80 points, which fulfills the course part of the Ph.D. degree.

Service to the Department

- Automatic Control, Basic Course (AK) (2)
- Real-Time Systems (1)
- Computer Controlled Systems (1)
- Dynamics and Control (BEST Summer School) (1)

Work on computer based interactive learning tools for control education in general, and for the Basic Course in particular, has resulted in the software package Ictools. The project attracted attention and was presented in Zackrisson (1997). A full presenteation of the project was presented in the journal paper Johansson *et al.* (1998).

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Analysis and Synthesis of Piecewise Linear Systems

Sven Hedlund

Keywords: Piecewise Linear Systems, Fuzzy Control, LMI
Supervisors: K. E. Årzen, A. Rantzer.
Start of project: 970901
Course Points: 10
Publications: –
Plans: Lic 000301, Dr 020901

State of the art

The theory for linear control systems is well-developed, and linear control techniques are being successfully used in a large number of applications. For processes with severe nonlinearities, however, the theory is substantially less powerful, and much research remains to be done. Even fundamental questions such as stability of nonlinear systems cannot easily be addressed.

A natural and powerful extension of linear system theory is to consider systems with piecewise affine dynamics. Such systems arise naturally from linear systems with actuator constraints and gain scheduled controllers and can also be used as approximations of other nonlinear systems.

Anders Rantzer and Mikael Johansson have done some work on piecewise linear (pwl) systems using linear matrix inequalities (LMIs). A result of this is that there are now techniques for analysis of stability, observability, reachability, input-output gain. There are also methods for the synthesis of optimal controllers.

Goal

There are several possible continuations to the work that has been done so far on pwl systems. Below are some issues which suffer a lack of knowledge listed.

- How to handle reference signals.
- Model uncertainty.
- How to coordinate the LMI solver and the pwl problem formulations for efficient computations.
- Optimal control with constraints on the control signal.

- The theory is developed for continuous systems so far. Is it possible to extend the results to discrete time systems?

I want to investigate as many as possible of these issues.

Research Approach

In addition to the support I rely on from my supervisors, I will try to track and to keep up with similar work that is done by other researchers. I intend to take courses, deepening my insight in the problems that I will face.

Milestones

- An internal report on the Piecwise Linear Toolbox will soon be finished.
- A conference paper on the PWL Toolbox will be written for the 14th IFAC World Congress, Peking, July 1999.
- A FAMIMO (cf External Contacts) benchmark, control of a gasoline direct injection engine, should be completed before jan 1999. Little work has been done on this till now.

Results

Working in the FAMIMO project (cf External Contacts), I have developed a toolbox for computational analysis of pwl systems based on the theory developed at our department. The toolbox can also be used for modeling, simulation, and optimal control of pwl systems.

External Contacts

My work is financed by the EU research project FAMIMO, Fuzzy Algorithms for Multiple Input Multiple Output systems. This is possible thanks to the close connection between fuzzy systems and pwl functions.

FAMIMO aims at designing fuzzy systems for reliable control of complex processes. The partners will develop some methods they have preferentially studied and all resulting methods will be tested on two multivariable nonlinear processes (benchmarks) which both have strong industrial relevance despite the difficulty to obtain a precise mathematical description.

In the summer of 1998 I will visit Tokyo Institute of Technology in Japan to do a joint research with the Department of Control Systems Engineering. I will also visit some other departments to learn about their work and to present the Piecewise Linear System Toolbox.

Course Work

As of the 27th of May 1998 I have 10 points and at the end of the spring semester I aim to have 20 points.

Service to the Department

I have taught the following courses:

Dynamics and Control, BEST summer course

Automatic Control, Basic Course (FRT010 Reglerteknik AK)

Computer-Controlled Systems (FRT020 Digital reglering)

References

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Draft Copy.

Computational Analysis of Piecewise Linear Systems

Mikael Johansson

Keywords. *System Analysis, Piecewise Linear Systems, Convex Optimization*

Thesis Advisors: *K.-E. Årzén and A. Rantzer.*
Start of project: *940831*
Course Points: *Around 60.*
Publications: *5 journal papers, 4 reports, 1 book chapter, 9 conference papers and 2 abstracts.*
Plans: *Dr 98*

State of the art

The theory of linear control systems is well founded, and linear control theory has proven to be a powerful tool for designing controllers for a vast range of industrial processes. The common practice is to approximate the system dynamics close to some operating point by a linear system, which is then analyzed using linear analysis tools. As demands on system performance increases, however, controllers are required to work over large operating ranges where the assumption of linear dynamics is no longer valid. Successful design and tuning of such controllers is strongly dependent on an ability to analyse the nonlinear effects that arise off the equilibrium. Moreover, even for systems with linear dynamics, virtually no controllers end up being linear at implementation. Due to signal limitations, safety considerations and other issues not easily dealt with using basic control theory, the initial control algorithm is often augmented by logic rules. The resulting combination of linear dynamics and logic rules leads to a potentially complex dynamic behavior, for which the standard analysis tools are often found to be insufficient. To verify the system behavior, one then has to resort to excessive simulations. As an increasing part of product value is invested in software, there is a strong economical interest in more refined methods for analysis of dynamical systems with switching and logic.

An interesting system class for studying these issues is the class of *piecewise linear systems*. They are convenient for expressing the combination of linear dynamics and switching logic, and are general enough to approximate any smooth nonlinear system to arbitrary precision. Although hopelessly general at a first glance, piecewise linear systems enjoy some (local) linearity and convexity properties, which are very useful in the development of efficient analysis methods.

The research on piecewise linear systems has a long history within control theory. One of the first occurrences of the phrase "piecewise linear" in control theory can be found in the book by Andronov [?], that uses ideas from Poincaré to analyse oscillations in piecewise linear systems. Early attempts to develop an qualitative understanding of piecewise linear systems were also made by Kalman [?] , who tried to predict the qualitative behavior of saturated systems using the singular points of the dynamics in different operating regions. It would, however, take several decades before these ideas where refined and formulated into analysis tools for more general piecewise linear systems. In the meantime, developments on piecewise linear systems appeared almost exclusively as work on linear systems interconnected with static nonlinearities, such as relays, saturations and friction. However, rather than recognizing the common features of these problems (all being piecewise linear), the analysis of each of these components branched into more or less isolated bodies of research. Since the effects on friction, saturations and relays in linear systems turned out to be very challenging to analyze, these research directions have remained very active areas of research with many important problems left unsolved. Several theoretical results with broader applications has come out of these lines of research, notably in the work on optimal control [?], absolute stability [?] and differential equations with discontinuous right hand sides [?], but there appears to have been no attempts to extend these results into tools that would apply also to more general piecewise linear systems.

It is fair to say that it was the circuit theory community who first recognized piecewise linear systems as an interesting system class in its own right. Driven by the need for simulation and analysis of circuits with diodes and other piecewise linear elements, a considerable research effort has focused on efficient representation of piecewise linear systems [?, ?]. The analysis problems have mainly been concerned with static problems and DC analysis [?], while the more complicated dynamic behaviors have remained largely unattended.

Triggered by the recent increase in the use of switched and hybrid controllers, two conceptually different approaches to analysis of general piecewise linear dynamical systems have emerged. For discrete time dynamics, some attempts have been made to formulate analysis procedures based on properties of affine mappings and polyhedral sets [?]. This approach captures some unique features of piecewise linear systems, but has unfortunately turned out to be hard to transform into practically applicable algorithms [?]. For continuous time dynamics, Pettit has developed a method for qualitative analysis of piecewise linear systems that is based on vector field considerations[?]. The approach can be seen as a multidimensional extension of phase portrait techniques and, in some sense, represents the most recent extensions and refinements of the work initiated by Kalman in the 50's. Using computations based on linear programming, graph theory, and manipulation of polyhedra, the computer tools developed by Pettit gives a qualitative picture of the overall dynamics, and indicate the presence of sliding modes, probable limit cycles and instabilities. The research monograph [?] forms a good starting point for research on piecewise linear systems, emphasizing many computational issues that are fundamental in the development of tools for piecewise linear systems.

When it comes to *quantitative* analysis of piecewise linear systems, there are virtually no results available. Recently, the theoretical research on hybrid systems has provided a number of interesting Lyapunov-like results[?], but no computational stability tests are available, and quantitative analysis of piecewise linear systems remains far from the simplicity of solving a Lyapunov equation for assessing stability of a linear system.

Goal

The aim of this project is to derive efficient computational procedures for quantitative analysis of piecewise linear systems. These methods should account for uncertainties and external disturbances, and should be possible to incorporate into standard computational environments for control systems design.

Research Approach and Results

This research grew out of a project on analysis and design of fuzzy controllers. Such systems produce mappings which are piecewise linear in the large [Joh94, Joh95, Joh96], and thus the need for quantitative analysis of piecewise linear systems was identified. For such systems, it was natural to consider Lyapunov functions that are *piecewise quadratic*. In the report [JR96a], we showed that such Lyapunov functions could be computed using convex optimization. More specifically, it is possible to formulate the search for a piecewise quadratic Lyapunov function for a piecewise linear systems using linear matrix inequalities (LMIs) [JR96b, JR97a, JR98]. The stability results were extended to system analysis problems in [RJ97a, RJ97b], which also contained a procedure for design of suboptimal controllers for piecewise quadratic criteria. Issues that arise when the method is applied to smooth nonlinear systems was discussed in [JR97b, RJ97b]. The format for piecewise quadratic Lyapunov functions encompasses the important special cases globally quadratic and piecewise linear Lyapunov functions. By restricting the format and consider Lyapunov functions that are piecewise linear, the necessary computations can be carried out using linear programming, as described in [Joh98]. The results have been packaged into a Matlab toolbox by Sven Hedlund during 1998[HJ99]. The results for piecewise linear systems has with minor modifications found their way back to the analysis of fuzzy systems that triggered the initial research [JMR+97, ÅJB97, Joh97, JRÅ98a, JRÅ98b].

I have also been involved in the development of interactive learning and design tools for control. This work has been done together with Magnus Gáfvert and Karl Johan Åström, and has resulted in a number of publications [JÅ96a, JÅ96b, JGÅ98, WHJ98].

Milestones for Future Work

1. Thesis write-up.
2. Finalizing my PhD degree and broaden my profile by taking courses in Signal Processing, Mathematical Statistics and Computer Science.

External Contacts

Academic Contacts. During my studies, I have spent two longer periods abroad;

- I visited professor Li-Xing Wang at Hong Kong University of Science and Technology, Hong Kong, China, for three months in 1995.
- I visited prof. Romeo Ortega at Supelec, Paris, France, during six months 1998.

Industrial Contacts. I have or have had projects with the following companies:

- Volvo Technical Development,
- ABB Industrial Systems,
- Comsol Europe AB,
- CelsiusTech, and
- Perstorp Tecator.

Other Contacts. I have also been working within two European research programmes, FALCON and FAMIMO, both concerning the design and tuning of fuzzy control systems, and I am member of the recently founded IFAC Technical Committee on Neural and Fuzzy Systems.

Course Work

Approximately 60 course credits.

Service to the Department

Teaching Services. I have been teaching the following courses: Reglerteknik AK, Computer Controlled Systems, Real Time Systems, and Nonlinear Control Systems.

Course Development. I developed and implemented new educational software for the basic course and for the course on nonlinear systems. I also wrote a new exercise compendium for the nonlinear systems course.

Thesis Supervision. I supervised masters students Rui Paiva and Berndt Trageser.

References and Publication List

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Grafchart for Recipe-Based Batch Control

Charlotta Johnsson

Keywords: Batch control, Batch recipe, Grafcet, Petri nets, Supervisory control, Sequential control.
Supervisors: Karl-Erik Årzén
Start of project: 9308
Course Points: 88
Publications: 5 paper, 11 conference papers, 1 licentiate thesis
Plans: Dr VT1999

State of the art

Several commercial batch control systems exist today. The batch recipe structuring parts are all very look alike. A graphical language consisting of steps and transitions is most often used. However, no linking to the theory of Grafcet and Petri nets is thought of, neither what concerns analysis or formal description. The linking between the recipe and the actual equipment control is most often not very clear.

The graphical representation of a recipe is, in systems of today, combined with a textual representation containing the information that is not traditionally stored within the graphics.

Goal

Grafchart and High-Level Grafchart allows for a more compact, but still clear and intuitive graphical representation of the recipes. The language can be used both on the recipe structuring level and on the equipment control level, giving a clear linking between the two levels. Grafchart and High-Level Grafchart are founded on Grafcet and Petri nets, thus the theoretical work performed in these areas can be used.

Goals achieved:

- Formal description of Grafchart.
- Syntax and semantics of High-Level Grafchart.
- Batch recipes structured with Grafchart and High-Level Grafchart.
- Licentiate thesis, presented 970606.

Goals to achieve:

- Formal Analysis of batch recipes (50% done).
- Formal Description of Grafchart and High-Level Grafchart (50% done).
- Link to Supervisory Control à la Grenoble.
- Write thesis.

Research Approach

This project has a steering committee with members from both suppliers and users of batch control systems. Meetings with the steering committee are held twice a year. The steering committee gives valuable information about existing batch recipe systems and it gives feedback on the work that is performed within the project.

Grafchart and High-Level Grafchart as well as the different recipe structuring alternatives are implemented in G2.

Industrial visits to leading batch control system vendors gives important information and allows for the recipe structuring ideas within the project to be known in industry.

Milestones

June 98	Write Introduction and Industry Practice.
July 98	Formal analysis completed.
August 98	Write Comparison Grafcet - Grafchart and Petri net - HL Grafchart.
September 98	Vacation
October 98	Formal description completed.
November 98	Look at Supervisory Control à la Grenoble.
December 98	Writing completed.

Results

The graphical language Grafchart and High-Level Grafchart is aimed at sequential control applications at the local and the supervisory control level. The main application has been recipe-based batch control. The language together with ideas of how it can be used to structure batch recipes are presented in Johnsson and Årzén (1994), Årzén and Johnsson (1996a), Årzén and Johnsson (1996b) and Johnsson and Årzén (1996a). In Johnsson and Årzén (1996b) some object-oriented extensions to Grafchart are presented and discussed.

Grafchart and High-Level Grafchart has been used for more applications than batch recipe structuring. These are presented in Årzén and Johnsson (1997) and Johnsson and Årzén (1998c).

In the spring of 1995 I visited Purdue University, IN, USA, and Prof. V. Venkatasubramanian for three month. The stay resulted in two journal articles to be published in `Computers and Chemical Engineering`, Viswanathan *et al.* (1997) and Johnsson *et al.* (1997), and one conference presentation Sviswanathan *et al.* (1996). The work treats the tasks of how to automatically generate a batch recipe from a formula description.

Jo Simensen, a Norwegian PhD-student from NUTH, visited us for three month in the fall of 1996. His stay resulted in a joint paper, Simensen *et al.* (1997), and an internal report, Simensen *et al.* (1996). The work concerns multi-view information models for batch plants.

In June 1997 I presented my licentiate thesis, Johnsson (1997). The results presented in the thesis were rewritten into a journal article, Johnsson and Årzén (1997). The article will be published in `Computers and Chemical Engineering` in 1998. The results were also presented at the `World Batch Forum meeting`, ?, in Baltimore USA and at `ADPM'98` in Reims, France. The ADPM'98 paper was selected to be published in an extended version, Johnsson and Årzén (1998d), as a journal article in `European Journal of Automation`.

Recently, I started to look at formal analysis of batch recipes structured with Grafchart using the analysis methods of Petri nets. The first results are presented in Johnsson and Årzén (1998a). The similarities and differences between Grafchart and Grafcet/Petri nets are presented and discussed in Johnsson and Årzén (1998b).

External Contacts

- **Universities:**

LAG, ENSIEG, Grenoble, France	Several visits
Chalmers, Göteborg, Sweden	

- **Industries:**

ABB Industrial Systems	Steering committee
Alfa-Laval Automation	Steering committee
Astra Production Chemicals	Steering committee
Kabi Pharmacia	Steering committee
Van den Berghs Food	Steering committee

Novo Nordisk, Denmark
Gensym, Sthlm, Sweden
Tetra Laval, Lund, Sweden

GSE Systems, MD, USA	Visited 9805
PId Inc, AR, USA	Visited 9805
Intellution, MA, USA	Visited 9805
Foxboro, MA, USA	Visited 9805
Gensym, MA, USA	Visited 9805

Course Work

I have more than 80 points, I do not intend to follow any courses during HT98 or VT99.

Service to the Department

AK-efd	HT94, HT95, HT96, HT97
AK-M	HT93
PR-K	VT94, VT98
DigReg	VT95, VT96
Identification	VT97

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Harmonic Analysis of Electric Power Distribution Networks

Erik Möllerstedt

Keywords: power networks, modelling, nonlinear analysis, simulation, system identification.
Supervisors: B. Bernhardsson, A. Rantzer.
Start of project: 950701
Course Points: 56
Publications: 1 licentiate thesis, 2 technical reports, 5 conference papers
Plans: PhD Spring 2000

State of the art

The use of power electronics have given possibilities for more sophisticated control of power networks. This creates new demands on power network modelling. The models used today were developed for simulation of systems containing one or a few nonlinear components, whereas modern distribution networks contain numerous nonlinear and switching loads. These networks cannot be modelled in detail, which brings up the need for methods to aggregate nonlinear loads. The models must not only allow for efficient and accurate simulation, but also be suitable for analysis and control design.

Goal

The aim of the project is to develop methods to analyze and simulate modern distribution networks, which contain numerous nonlinear and switching components.

Goals achieved:

- A model structure for nonlinear and switching loads, the Harmonic Norton Equivalent. The structure supports aggregation of loads.
- A procedure for experimental estimation of model parameters.

Goals to achieve:

- *error analysis:* How are the errors introduced by the linearization and the truncation affected by the aggregation of loads?

- *stability analysis:* How can ideas from stability analysis of linear systems be used to analyze the proposed models?
- *resonances:* How are resonance problems detected and solved?
- *filter design:* How should filters for harmonic mitigation be designed?
- *transient analysis:* The model structure is derived for steady state analysis. Is it possible to use it for transient analysis too?
- *improved experiments:* Are there more simple ways to obtain the models from measurements?

Research Approach

We intend to use the developed model structure to extend stability and robustness results from linear control theory. There is some theoretical work done on nonlinear systems with periodic inputs, that can suit our needs.

Milestones

- Write 1-2 journal articles on my licentiate work.
- Conclude the research on electric networks for trains in collaboration with Daimler-Benz, Berlin, and Adtranz, Zürich. Result: journal article and chapter in thesis.
- article on stability and robustness analysis, and error analysis. What errors are introduced when using Harmonic Norton Equivalents, and how do they affect the analysis.

Results

My licentiate thesis Möllerstedt (1998) is based on two conference papers Möllerstedt *et al.* (1997d); Möllerstedt *et al.* (1997a) and two technical reports Möllerstedt *et al.* (1997b); Möllerstedt *et al.* (1997c). A model structure for highly nonlinear components has been developed. The model structure, called Harmonic Norton Equivalent, addresses two problems that are central in control theory, namely model reduction and system identification. It is essential to have simple representations of large systems, and there must be a way to obtain these simple models experimentally, as detailed modelling most often is too complicated. The Harmonic Norton Equivalent has its roots in the method of harmonic balance. It is a frequency domain description of loads in electric networks and describes a linear relation between the current spectrum and the voltage spectrum. The linearization implies that aggregation of loads for model reduction is a straightforward, non-iterative procedure.

The models can be obtained through analytical calculations, measurements or time domain simulations. A procedure for experimental estimation of model parameters is presented. The procedure is used to estimate the parameters of a dimmer model from measurements on a real dimmer. The obtained model shows a very good agreement with validation data.

External Contacts

Industry:

- Sydkraft AB: Daniel Karlsson, Magnus Akke
- Vattenfall AB: Anders Åberg
- Daimler-Benz: Henrik Olsson
- Adtranz: Marcus Meyer
- Elforsk AB: Sten Bergman

Academia:

- Dept of Industrial Electrical Engineering and Automation, LTH: Olof Samuelsson and Mats Alaküla
- Dept of Electric Power Engineering, KTH: Lennart Söder, Erik Thunberg, Lawrence Jones

Course Work

56 point (980901)

Service to the Department

Teaching Assistant in the following Courses: Automatic Control, Basic Course (2), Computer Controlled Systems (2), Adaptive Control (2), Process Control (1).

References

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PID Control

Hélène Panagopoulos

Start of project: 960131

Supervisors: Karl Johan Åström, Tore Hägglund.

Keywords: PID Control, Design, Automatic Tuning, Deadtime Compensation, Oscillatory Systems.

Course points: 56 points (980415).

State of the art

PID control is by far the most common control algorithm. Very much has been written about it, see for example the monograph Åström and Hägglund (1995). In spite of this there are no uniformly accepted design methods, neither is there a good characterization of the processes where PID control is appropriate. There are several reasons to look for better methods to design PID controllers. One reason is the significant impact it may give because of the widespread use of the controllers. Another reason is that emerging auto-tuners and tuning devices can benefit significantly from improved design methods.

Goal

The first goal of my research is to explore the limits of PID control, to characterize systems where PID control is appropriate, to develop design methods and to determine the minimal information required to tune a PID controller. The second goal is to investigate the modifications that are necessary to use PID control for systems with time delays and oscillatory systems.

To deal with systems with time delays the Smith predictor, see Smith (1957), unfortunately does not work for unstable processes for example processes with integration. Some methods have been suggested to overcome this difficulty Åström *et al.* (1994). My ambition is to investigate these kind of systems and try to find a systematic design method for them. I will also try to find a similar way to deal with oscillatory processes.

If successful my research will result in systematic design methods for PID control that can be used for automatic tuning. I will also have methods to extend PID control by filtering, dead time compensation and compensation for oscillatory systems.

Research Approach

My near term goal is to extend the results for PI control to PID control, to develop software for the design calculations and to evaluate the method. The obtained results will be used to develop simpler tuning rules. A nice feature of the method for the design of PI controllers is that it makes it also possible to deal with filtering of the data. This will also be done for the design of PID controllers. Also, a nice feature will be shown how traditional methods for design of PID controllers relates to robust H_∞ control, in particular the loop shaping methods developped in Vinnicombe (1998).

Furthermore, I will investigate what information about the process is required for design of PID controllers and too develop methods to derive this information from plant experiments. Hopefully, this will result in a licentiate thesis in the fall. After that I intend to investigate schemes for dead time compensation and control of oscillatory systems.

Milestones

- Systematic design method for PI and PID controllers.
- Systems with dead time.
- Oscillative systems.
- Software.

Results

Until today an efficient numerical method for designing PI controllers has been derived, see Panagopoulos *et al.* (1997a) and Åström *et al.* (1998). The design is based on optimization of load disturbance rejection with constraints on sensitivity and weighting of set point response. Thus, the formulation of the design problem captures three essential aspects of industrial control problems, leading to a non-convex optimization problem. Efficient ways to solve the problem has been developed. The results for the design of PI controllers have been documented in the full paper Åström *et al.* (1998) which is to be published in the May issue of Automatica, 1998.

External Contacts

Besides of the research on design of PID controllers, I have been in contact with an association of the Swedish pulp and paper industry, called Skogsindustriernas Tekniska AB (SSG). This has led to investigations of a design method for PID controllers called the Lambda method used by the pulp and paper industry. The results of investigations and new upcoming ones has been documented in an internal report, see Panagopoulos *et al.* (1997b).

Course Work

As of the 1th of April 1998 I have 49 points and at the end of the spring semester I aim to have 56 points.

Service to the Department

Teaching in the undergraduate courses AK and DR. Responsible for the material of the undergraduate courses.

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SMITH, O. J. M. (1957): "Closed control of loops with dead time." *Chemical Engineering Progress*, **53**, May, pp. 217–219.

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Control of Steel Processes

Lars Malcolm Pedersen

Keywords: Rolling Mill Thickness Control and Reheat Furnace Slab Temperature Control.
Supervisor: Björn Wittenmark.
Start of project: 920901 and 970401
Course Points: 67 (980701)
Publications: 2 journal articles, 8 conference papers, 1 internal report, and 1 Lic. Thesis (980701)
Plans: Dr. VT1999

State of the art

Rolling Mill Thickness Control

The purpose of the thickness control system is to compensate for elastic deflection of rolling mill when the plate thickness is reduced. The thickness can not be measured during rolling.

Today mainly PI controllers are used for the compensation for the rolling mill deflection. The plate thickness is estimated using a static relationship between the measured rolling force and the rolling mill deflection.

Reheat Furnace Slab Temperature Control

The purpose of the slab temperature control system is to control the furnace temperature in a number of furnace zones to obtain a desired final temperature profile of the slabs passing through the furnace. The slab temperature profile can not be measured.

Today the slab temperatures are normally controlled using simple weight functions and PI-controllers. The slab temperatures are normally estimated using finite difference models of varying complexity.

Goal

The goal of the research is to design and implement controllers for the thickness control system and reheat furnace using advanced methods for modeling, parameter estimation and control.

Research Approach

The controller design for the thickness control system is divided into the following phases

- Literature study of state of the art for control.
- Data collection from the thickness control system at The Danish Steel Works Ltd.
- Construction of multivariable and nonlinear mathematical model from physical relations for the processes.
- Identification of the parameters of the mathematical model.
- Design of multivariable and nonlinear controller for the thickness control process.
- Verification of controller performance by computer simulations.
- Implementation of a simplified version of the thickness controller.

The similar approach is taken for the for furnace control problem, except the controller is not implemented.

Milestones

A large part of the work has already been done and the remaining sub goals are

- Implementation of simplified version of thickness controller. Deadline: 011098.
- Verification of furnace controller performance by computer simulations. Deadline: 011298
- Preliminary version of Dr. Thesis finished. Deadline: 010199

Results

The main results of my research work is

- Modeling of thickness control system: Pedersen (1994), Pedersen (1995a), Pedersen (1995b), and Pedersen (1996).
- Controller design for thickness control system: Pedersen and Wittenmark (1996), Pedersen and Wittenmark (1998e), Pedersen and Wittenmark (1998b), and Pedersen and Wittenmark (1998d).
- Modeling and control of a double side shear, Pedersen and Villadsen (1997).
- Modeling and controller design for a reheat furnace, Pedersen and Wittenmark (1998c), and Pedersen and Wittenmark (1998a)

I would like to submit one or two more articles, if possible.

External Contacts

My external contacts are

- Employed as a process engineer at The Danish Steel Works Ltd.
- Participant in two MEFOS research projects on rolling mill control and furnace control.
- Assistant advisor in a Industrial Research Education Project involving Lindø Shipyards and DTU.
- Partner in ECSC proposal for a research project on thickness control coordinated by VDEh, Germany.

Course Work

I plan to have collected 80 course credits by 990101 by the following courses at HT98

- Synthesis (5 credits)
- Partial Differential Equations (5 credits)
- Literature study of furnace control, finalized by internal report. (3 credits)

Service to the Department

None.

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PEDERSEN, L. M. and B. WITTENMARK (1998e): "Thickness control for a plate mill." In *Automation in mining, mineral, and metal processing 1998.* IFAC.

Industrial Aspects of On-line Monitoring and Diagnosis

Mikael Petersson

Keywords: Diagnosis, monitoring, on-line, hig-level diagnostics, process industry, manufacturing lines industry
Supervisors: Karl-Erik Årzn
Start of project: 980101
Course Points: 7 p (980601), another 13 p within short
Publications: none
Plans: Licentiate spring semester 2000, PhD fall semester 2002

Introduction

Increasing demands on reliability, safety, environmental protection, and improved control of technical processes make on-line monitoring and diagnosis a very important part of industrial control systems.

Very few of the modern diagnostic methods that have found any industrial applications, despite the wide academic activity.

Goal

The aim is to study the industrial application aspects of different on-line monitoring and diagnosis methods. It is important to make a correct balance between the theoretical strength of the methods and their industrial relevance.

The first application that will be studied in the project is on-line diagnosis of discrete manufacturing lines consisting of industrial robot-based flexible production stations. A second process have been identified as the pulp & paper industry. High-level loop diagnostics have been suggested as an initial area of research.

Research Approach

The research focus will be in one or several of the following areas:

- Combined model-based and symptom-based diagnosis
- Hybrid diagnosis schemes

- Integrated control and diagnosis
- Diagnosis of mode-changing processes
- Integrated operation, diagnosis, and maintenance

Once the application has been decided upon a finer selection will be made.

Milestones

- Introductory overview - Fall 98
- Choose Application(s) - Summer/Fall 98

External Contacts

Mikael Petersson is employed by ABB Corporate Research, a division of Asea Brown Boveri AB.

The project will be performed in close connection with other ABB companies within the different application areas.

Course Work

As of the 28th of May 1998 I have 7 points and at the end of June I aim to have 20 points.

Nonlinear Control and Robotics

Anders Robertsson

Keywords: Robotics, Output feedback control, Model-based observers, Force control, Nonlinear Stabilization
Supervisors: Rolf Johansson
Start of project: 1993-10-01
Course Points: 85
Publications: 1 published, 2 submitted journal papers,
5 published, 6 submitted conference papers
Plans: PhD during summer 1999

State of the art

Even though industrial robots generally are equipped with accurate sensors for position measurements, velocity measurements are often absent or corrupted with a lot of noise. The alternative of numerically differentiating the accurate position signal may often work "good enough" in practice, but has drawbacks especially for very slow or fast velocities.

As for stabilization, there are many open issues. In contrast to the linear case, the certainty equivalence property doesn't hold. During recent years, both the regulation problem and the tracking problem have gained large attention for rigid robots as well as for robots with flexible joints, see [10],[2], and references therein, though still much remains to be done for the output feedback case.

Goal

As many control schemes require full state information it is of interest to investigate how the stability/robustness properties in these schemes are affected when we use estimated states instead. One of the the main questions which could be asked is: "Can we re-use control agorithms based on state feedback in combination with observers, and under what limitations?".

Some control principles, like "exact linearization"—*e.g.*, computed torque—have shown very poor robustness properties, while passivity based control appear to have better behaviour with respect to robustness and stability when used together with observers.

Goals achieved:

- Observer design and stabilization applied to a nonlinear kinematic model with resemblance to robot dynamics [13], [12], [14];
- Semiglobal results for robot control;
- Extensions of passivity results [4], [5].

Goals to achieve:

- Evaluation of observer-based control on an industrial robot;
- Force-control experiments;
- Global tracking control for robots.

Research Approach

We use nonlinear theory for (model based) observer design and stabilization; Passivity-based control [2], [1], Input-to-State-Stability [15] and Lyapunov techniques, e.g. back-stepping [9], [13], [12], [14].

Regarding the model classes, we have particular emphasis on so called Euler-Lagrange systems and systems which can be partitioned in linear and nonlinear parts.

Milestones

spring 98	Writing papers and thesis
summer 98	Application: Force Control experiments
summer 99	Dissertation

Results

During 1993-1996 I have worked in the NUTEK project *Lund Research Programme in Autonomous Robotics,* (RAS), which resulted in the Open Robot Control System, [11]. The project has also brought us to an integration of resources from the Dep. of Automatic Control, Dep. of Industrial Electrical Engineering and Automation, and the Dep. of Production and Materials Engineering. The project has been extended for another three-year-period. System identification experiments for controller tuning in the Robotics lab are addressed in [6], [7].
See also "Goals achieved" above.

External Contacts

Before I started as a PhD student in Lund, I spent a year in professor P. Kokotovic's group (CCEC) at UCSB. During 1995 and 1996 I have visited the department of Applied Mathematics, University of Twente, during all together a couple of months, where I have worked together with professor H. Nijmeijer, on observers and synchronization. During June 1998 a PhD student from Twente, A.J.J. Lefeber, will visit Lund.

Through the research project (RAS) there is a natural coupling to our industry partner; ABB Robotics (Dr. Torgny Brogård).

Course work

At the end of the spring term I will have 85 points, so I do not have any plans on taking additional courses.

Service to the Department

I have been a teaching assistant in the following courses:

Nonlinear Control and Servo Systems (2)	Adaptive Control (1)
Computer Controlled Systems (1)	Basic Course FED (3)
Basic Course M (3)	

In addition to this, there has been a lot of work in the Robotics lab, ranging from programming to electronics (re-)design. Extending the robot control system, under supervision of K. Nilsson such as adding support modules for system identification, adding interface for interaction with the real-time system Pålsjö, and writing base classes for the robot system in PAL, including the gripper and the force/torque sensor.

I have also participated as advisor in a couple of Master Thesis projects and supervised several student projects related to the Robotics lab.

References

[1] S. Battilotti, L. Lanari, and R. Ortega. "On the role of passivity and output injection in the output feedback stabilisation problem: Application to robot control." *European Journal of Control*, 1997.

[2] H. Berghuis. *Model-based Robot Control: from Theory to Practice.* PhD thesis, University of Twente, The Netherlands, 1993.

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[5] R. Johansson and A. Robertsson. "Stability analysis of adaptive output feedback systems." In *IEEE Conf. Decision and Control (CDC'98); (submitted to review)*, 1998.

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[10] A. Loria. *On Output Feedback Control of Euler-Lagrange Systems.* PhD thesis, Universite de Technologie de Compiegne, France, 1996.

[11] K. Nilsson, A. Robertsson, and R. Johansson. "Robot control research in Lund." In *Preprints, Reglermöte-94*, October 1994. Västerås, Sweden.

[12] A. Robertsson and R. Johansson. "A note on "nonlinear control using only position feedback: An observer backstepping approach"." In *Proceedings of "Robotikdagarna 1997"*, pp. 1–6, June 1997. Linköping, Sweden.

[13] A. Robertsson and R. Johansson. "Comments on 'Nonlinear output feedback control of dynamically positioned ships using vectorial observer backstepping'." In *IEEE Transactions on Control Systems Technology*, vol. 6, pp. 439–441, 1998.

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[15] E. Sontag. "On the input-to-state stability property." *European Journal of Control*, No 1, 1995.

Modeling of Thermo-Hydraulics

Hubertus Tummescheit

Keywords: physical models, thermo-hydraulics, object-oriented methods.
Supervisors: K. J. strm and J. Sternby
Start of project: 960415
Course Points: 30
Publications: 1 paper, 4 conference papers (980501)
Plans: Dr HT 2001

State of the art

Dynamic simulation packages for thermo-hydraulic systems (power plants, refrigeration equipment, heat exchanger networks, pipeline systems for gas and oil, district heating networks, HVAC systems) are usually

1. only for a specific application domain (APROS, Sinda/Fluint, TRANSYS),
2. lack interfaces for interaction with other software,
3. not designed with respect to solving control problems.

Some of these packages have very efficient numerical solvers, which are needed for simulating large plants, but they are specialized and restricted to narrow problem classes.

Goal

Design and implement a well validated, easy to use model library for the dynamic simulation of thermo-hydraulic processes. The library should be applicable to the physical model layer of all the above application domains and cover models both for design simulation and control design. The efficiency and the accuracy of the solution should be comparable to special purpose packages.

Research Approach

Describe how you intend to reach your goals. One of the foundations of modeling thermohydraulic processes are fast and accurate models of the thermodynamic properties of fluids. Almost all existing fluid models are not adapted to dynamic simulation, their numerical properties promise trouble and long simulation times. The solution of this problem for a substantial group of technically important fluids is a prerequisite to the goal. Building on these medium models, a base library for the typical equipment in thermo-hydraulic systems will be implemented in close cooperation with Jonas Eborn.

- Adapt current medium models to be suitable to dynamic simulation. Both completeness and efficiency are concerned. Discussion with NIST (National Institute of Standards in Technology) has started on requirements for their medium property routines.
- Using and exploring Modelica's new language features, apply object oriented techniques (analysis and design) to physical modeling of thermo-hydraulic systems.
- Verify the approach with application examples from several domains, currently it is planned to implement models for compression refrigeration cycles and steam boilers.
- Exploit "weak coupling" of variables through models, that use the most orthogonal set of state variables and test the result with numerical routines, that utilize this information.

Milestones

- Medium models: cooperate with NIST on suitable models for thermo-hydraulics.
- Thermo-hydraulic library, including medium models by end 98.
- Application test cases using the thermo-hydraulic library: summer 99
- Licenciate thesis: early 99.

External Contacts

Clemens Klein-Robbenhaar, GMD-FIRST, for methods on how to exploit "weak coupling" between thermal and hydraulic variables. Gerhard Schmitz, TU Hamburg-Harburg, HVAC of Aircraft. Mark McLinden, NIST, Boulder Colorado, Medium Properties for Refrigerants. Njal Pettit and Jakob Fredsted, Danfoss, and Arne Jacobson, DTU, Modeling of Refrigeration equipment.

References

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[2] Achim Sydow, editor. *Proceedings of the 15th IMACS world congress on Scientific Computation, Modelling and Applied Mathematics*, volume 6, Berlin, Germany, 1997. Wissenschaft und Technik Verlag.

[3] Hubertus Tummescheit. Objektorientierte modellierung thermohydraulischer systeme. *To appear in: Automatisierungstechnik*, 1999.

[4] Hubertus Tummescheit, Matthias Klose, and Thilo Ernst. Modelica and smile – a case study applying object-oriented concepts to multi-facet modeling. In Hahn and Lehmann [1], pages 122–126.

[5] Hubertus Tummescheit and Robert Pitz-Paal. Simulation of a solar thermal central receiver power plant. In Sydow [2], pages 671–676.

Autonomous Control

Anders Wallén

Keywords: Autonomous control, Intelligent Control, Sequential Control, Loop assessment, Performance assessment, Loop monitoring, PID control.
Supervisors: K. J. Åström, T. Hägglund.
Start of project: 911001
Course Points: 80+
Publications: 1 book chapter, 5 conference papers
Plans: PhD Spring 99

State of the art

A typical plant in process industry consists of several hundreds or thousands of control loops, typically with PID controllers. Thus, the operators and process engineers will not be able to spend too much time with each loop. As a result, many of the control loops perform far from optimally. It would be of great help if the control system itself took care of basic features like loop assessment, automatic tuning, performance monitoring and fault diagnosis. Today's systems have none or very little support for this.

Goal

To present a concept with a single loop controller, surrounded with additional functionality to make it behave in an autonomous or "intelligent" manner. The added intelligence should replace and/or facilitate the operator's interaction with the control loop.

Research Approach

The main approach has been to motivate autonomous controllers by examples. A platform has been developed in G2 using the Grafchart toolbox written by Karl-Erik Årzén. Different methods have been incorporated, for example:

- Assessment of input non-linearities such as backlash and friction, often present in control valves.
- Automatic $\kappa\tau$ tuning using relay feedback together with a closed loop step response.

- Detection of control loop oscillations.
- Scheme for automatic diagnosis of oscillations induced by valve friction.

Milestones

Writing thesis. During the fall I also intend to study ways of measuring how well a PID controller performs compared to what you would expect according to the design criteria.

Results

Different aspects of autonomous control systems have been studied. A couple of demonstrators have been implemented in order to illustrate software structuring principles and give examples of desired functionality. It has been shown how High-level Grafcet can be used for structuring and scheduling algorithms. A tool for simple process identification from step response data has been developed using MATLAB.

External Contacts

I visited Prof. Venkatasubramanian at Purdue University April – June 95. I worked together with PhD student Dinkar Mylaraswamy in a project on neural nets for fault diagnosis [Mylaraswamy *et al.* (1996)].

Apart from that, the informal contacts I have had with people from process industry, for example Börje Eriksson from MoDo, have been very valuable in order to get both feedback and new ideas.

Course Work

I do not intend to take any more courses.

Service to the Department

I have been teaching assistant in the following courses:

AK (5 times)

Real-Time Systems (3 times + additional project supervision)

Computer Controlled Systems (4)

Further, I have developed two laboratory experiments in CCS, one in Real-Time Systems, and (modification of) one in Process Identification. I was administrating the programs for the PC lab for $\approx$ 2 years. I was responsible for the seminar documentation also for $\approx$ 2 years.

References

ÅRZÉN, K.-E., A. WALLÉN, and T. F. PETTI (1995): "Model-based diagnosis—state transition events and constraint equations." In TZAFESTAS AND VERBRUGGEN, Eds., *Artificial Intelligence in Industrial Decision Making, Control and Automation*. Kluwer Academic Publishers.

MYLARASWAMY, D., A. WALLÉN, V. VENKATASUBRAMANIAN, and K.-E. ÅRZÉN (1996): "A model-based hybrid neural network architecture for fault diagnosis." In *AIChE Annual Meeting*. Miami Beach, Florida.

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WALLÉN, A. (1994): "Structuring control algorithms using grafcet." In *Reglermöte 94*. Västerås, Sweden.

WALLÉN, A. (1995): "Using Grafcet to structure control algorithms." In *Proceedings of The Third European Control Conference*. Rome, Italy.

WALLÉN, A. (1997): "Valve diagnostics and automatic tuning." In *Proceedings of the American Control Conference*. Albuquerque, New Mexico.

Control of *E. coli* Cultivations

Mats Åkesson

Keywords: Process control, modeling, fed-batch cultivation, *Escherichia coli*, substrate feeding, recombinant protein production.
Supervisors: P. Hagander
Start of project: 940901
Course Points: 68 (980501)
Publications: 1 licentiate thesis, 5 conference papers (980501)
Plans: PhD Dec 1999

State of the art

Large-scale production of many proteins can today be made using genetically modified microorganisms. One of the most frequently used host organisms is the bacterium *Escherichia coli*. A problem encountered during cultivations of *E. coli* is the accumulation of the by-product acetate, which tends to reduce growth and protein production. Formation of acetate can be avoided by a proper substrate feeding strategy, but most strategies require considerable process knowledge to work well. The main problem is that many important process variables cannot be measured on-line, which complicates the design and realization of a feedback strategy.

Goal

The goal of this project is to develop a robust feedback strategy for substrate feeding in *E. coli* cultivations. An important aspect is to develop tuning rules that requires a minimum of process specific knowledge. Such a methodology will be a valuable tool for cutting the development time for new processes.

Results

The results so far in the project are summarized in a licentiate thesis. The thesis presents a novel feedback strategy for substrate feeding in cultivations of *E. coli*. The key idea is to exploit a characteristic change in the cell metabolism at the onset of acetate formation. By superimposing short pulses in the substrate feed rate, on-line detection of acetate formation can be made using a standard dissolved oxygen sensor. Several experiments confirm the validity of this detection method.

A simple feedback algorithm is used to adjust the feed rate to avoid acetate formation while maintaining a high cell growth rate. The feasibility of the feeding strategy is demonstrated by simulations and tuning rules that require a minimum of process specific information are derived.

The feeding strategy requires good control of the concentration of dissolved oxygen. Variations in oxygen dynamics during a cultivation may cause problems if a controller with fixed parameters is used. A control approach based on PID control and gain scheduling from the stirrer speed is suggested.

Milestones

In the sequel of the project the following issues should be treated:

- Implementation of the control algorithm on a real process and development of appropriate safety nets.
- Investigation of the feasibility to use the method in large-scale reactors.
- Including effects from acetate consumption and recombinant product formation in the process model.
- Is it possible to extract more information from the detection method and thereby improve the control performance?

External Contacts

The project is performed in collaboration with Pharmacia & Upjohn, Bioprocess Development, Stockholm, Sweden, and the Department of Biotechnology, Lund University, Lund, Sweden.

During April 1998 a longer stay was made at the Center for Agricultural Biotechnology and Department of Chemical Engineering, University of Maryland at College Park, MD, USA.

Course Work

As of the 1th of May 1998 I have 68 points and at the end of the autumn semester I aim to have 80 points.

Service to the Department

Teaching assistant in the following courses: Computer-Controlled Systems, Automatic Process Control, Automatic Control (Basic Course).

Development of laboratory experiments in Automatic Process Control and Automatic Control (Basic Course).

Responsible for seminar documentation (1995).

References

Papers at International Conferences

[1] M. ÅKESSON, A. TOCAJ, P. HAGANDER, and J. P. AXELSSON. "Acetate formation and dissolved oxygen responses to feed transients in *Escherichia coli* fermentations: Modeling and experiments." Accepted to *the 7th International Conference on Computer Applications in Biotechnology*. Osaka, Japan. June 1998.

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[4] M. ÅKESSON, E. GUSTAFSSON, and K. H. JOHANSSON. "Control design for a helicopter lab process." In *Proceedings of the 13th IFAC World Congress*, San Francisco, USA, July 1996.

[5] E. FERRET, M. ÅKESSON, and A. CHÉRUY. "Process control: Performance analysis of an original approach taking into account the positivity constraints on process variables." In *Proceedings of the 3rd European Control Conference*, Rome, Italy, September 1995.

Conference Abstracts and Workshop Papers

[1] M. ÅKESSON, P. HAGANDER, and J. P. AXELSSON. "A probing approach for detection of acetate formation." Submitted to *Reglermöte '98*. Lund, Sweden. June 1998.

[2] M. ÅKESSON, P. HAGANDER, and J. P. AXELSSON. "A pulse technique for control of fed-batch cultivations." In *Abstract book of 8th European Congress on Biotechnology*, Budapest, Hungary, August 1997.

[3] M. ÅKESSON. "Integrated control and diagnostics using robust control methods." In *Proceedings of the EURACO Workshop Robust and Adaptive Control of Integrated Systems*, Herrsching, Germany, October 1996.

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[1] M. ÅKESSON. "A probing strategy for substrate feeding in *Escherichia coli* cultivations." Licentiate Thesis ISRN LUTFD2/TFRT--3220--SE, Department of Automatic Control, Lund Institute of Technology, Sweden, March 1998.

[2] M. ÅKESSON and P. HAGANDER. "Control of dissolved oxygen in stirred bioreactors." Technical Report ISRN LUTFD2/TFRT--7571--SE, Department of Automatic Control, Lund Institute of Technology, Sweden, February 1998.

[3] M. ÅKESSON. "Integrated control and diagnostics using robust control methods." Technical Report ISRN LUTFD2/TFRT--7552--SE, Department of Automatic Control, Lund Institute of Technology, Sweden, October 1996.

[4] M. ÅKESSON. "Etude comparative des performances et propriétés de la commande L/A, (Comparative study of L/A control).". Master's thesis ISRN LUTFD2/TFRT--5511--SE, Laboratoire d'Automatique, Grenoble, France, and Department of Automatic Control, Lund Institute of Technology, Sweden, 1994.