Research Abstracts 1999 - PhD Projects in Automatic Control

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Abstract

This report contains research summaries of the 17 PhD projects that were active at the Department of Automatic Control in June 1999.

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Contents

Modeling with Quantified Accuracy

Lennart Andersson

Start of project	1993-10-01	**Plan**	PhD Sep 1999
Supervisor	A. Rantzer	**Course Credits**	84
Publications:	1 Lic thesis, 2 journal articles, 6 conference articles.		

Research Problem and State of the Art

The research problem is simplification of uncertain and nonlinear models. Model simplification is important in modern control engineering in order to efficiently use the available analysis and design tools.

Today there are many useful methods available for obtaining simplified models, in particular for standard linear time-invariant models. However, for more complex models such as models with uncertainty there still remains a lot to be done.

Goals

Goals achieved:

- Survey of existing simplification methods in control
- Error bounds for uncertain and nonlinear models
- Frequency dependent error bounds for uncertain linear models
- Robustness of equilibria in nonlinear systems
- Application example in power systems

Research Approach

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

Results

My first work at the department was together with Anders Hansson on Extreme value control. An optimal control problem was solved numerically based on the Bellman equation. This resulted in my master thesis, [Andersson, 1993], and the

conference papers, [Andersson and Hansson, 1994b; Andersson and Hansson, 1994a].

In the spring 1995 I started doing research together with Anders Rantzer. We considered error bounds for 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 together with Carolyn Beck. This work resulted in the papers [Andersson and Beck, 1996b; Andersson and Beck, 1996a]. A journal article, [Andersson *et al.*, 1999], 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 resulting error bounds were published in the conference paper [Andersson and Rantzer, 1997] and in the journal article [Andersson and Rantzer, 2000].

During fall 1996 I sorted out some details and wrote my licentiate thesis, [Andersson, 1997], which I presented in January 1997.

Properties and further details of the error bounds were investigated during 1997. Some of these results are included in the report [Andersson and Rantzer, 1998].

During 1998 a summary of existing simplification methods in control was written, [Andersson, 1998].

Robustness of equilibria in nonlinear systems was investigated during the summer and fall 1998. Based on this work a conference article [Andersson and Rantzer, 1999a] and a journal article [Andersson and Rantzer, 1999b] were written. The results were applied to a power system model, [Andersson *et al.*, 1999], during spring 1999. This work was based on the master thesis [Lantz, 1997].

Milestone

PhD completed in September 1999.

External Contacts

I visited Caltech during the fall 1995, where I worked with Carolyn Beck. This work continued during her postdoc in Lund, spring 1995.

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

Course Work

I have obtained the 80 credits required for a PhD.

Service to the Department

Teaching

I have been a teaching assistant in the following courses

Course	Last Taught
AK(FED)	Fall 1998
Process Control	Spring 1998
Adaptive Control	Fall 1997
Nonlinear Control	Spring 1997
AK(M)	Spring 1997
Computer Control Systems	Spring 1996
Process Identification	Spring 1995

Initiatives

I have been involved in arranging the Lund-Lyngby day on control during the fall 1996 and spring 1997.

I have contributed to the development and improvement of course material in several courses; for example the rewriting of exercises in process control and the development of a laboratory exercise in process identification.

Administrative Duties

I was responsible for the documentation of written exams during 1994–1998.

Master Thesis Supervision

I supervised the thesis [Ahnelöv, 1995] and assisted in the supervision of the thesis [Lantz, 1997]. I have also supervised numerous projects in adaptive control and process identification.

Publications

Ahnelöv, M. (1995): "Tidsoptimering av en lödprocess.". Master's thesis ISRN LUTFD2/TFRT--5530--SE, Lund Institute of Technology.

Andersson, L. (1993): "Olinjär stokastisk reglering av extremvärden.". Master's thesis ISRN LUTFD2/TFRT--1993--SE, Lund Institute of Technology.

Andersson, L. (1997): *Comparison and Simplification of Uncertain Models.* Licentiate Thesis ISRN LUTFD2/TFRT--3216--SE, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Andersson, L. (1998): "A review of model simplification." Unpublished.

Andersson, L. and C. Beck (1996a): "Model comparison and simplification." In *35th IEEE CDC Proceedings.* Kobe, Japan.

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

Andersson, L. and A. Hansson (1994a): "Extreme value control of a double integrator." In *33th IEEE CDC Proceedings.* Orlando, Florida.

Andersson, L. and A. Hansson (1994b): "Olinjär extremvärdesreglering – ett exempel." In *Reglermöte.* Västerås.

Andersson, L., M. Lantz, and A. Rantzer (1999): "Robustness of equilibria in power systems." Unpublished.

Andersson, L. and A. Rantzer (1997): "Frequency dependent error bounds for uncertain linear models." In *American Control Conference*. Albuquerque, New Mexico.

Andersson, L. and A. Rantzer (1998): "Frequency dependent error bounds for uncertain linear models." Technical Report TFRT-7575. Department of Automatic Control, Lund Institute of Technology, Sweden.

Andersson, L. and A. Rantzer (1999a): "Robustness of equilibria in nonlinear systems." In *14th IFAC World Congress*. Beijing, China.

Andersson, L. and A. Rantzer (1999b): "Robustness of equilibria in nonlinear systems." Submitted to Automatica.

Andersson, L. and A. Rantzer (2000): "Frequency dependent error bounds for uncertain linear models." *IEEE Transactions on Automatic Control*, March. Accepted for publication.

Andersson, L., A. Rantzer, and C. Beck (1999): "Model comparison and simplification." *International Journal of Robust and Nonlinear Control*, **No 9**, pp. 157–181.

Lantz, M. (1997): "Robustness analysis using Omola with applications to power network.". Master's thesis ISRN LUTFD2/TFRT--5585--SE, Lund Institute of Technology.

Modeling drivers' longitudinal behavior

Johan Bengtsson

Start of project	April 1999	**Plan**	PhD 2004
Supervisor	R. Johansson and E. Hesslow	**Course Credits**	0
Publications:	0		

Research Problem and State of the Art

The project aims to design a driver model including a model of a human driver's behavior in traffic. The model should describe a human driver's longitudinal control of his vehicle related to a front vehicle. Typical situations that the model needs to handle are: the driver approaching another car; following the front car; a car cutting in from another lane; the front car braking hard. The model should represent the drivers behavior equally well in highway traffic and in urban traffic.

A model like this can be used as an instrument to improve driver comfort and the road safety as well as driving-support devices. In USA there was 2.2 million rear-end collisions in 1990 and nearly half of these collisions were due to drivers following their front car too closely.

Although scientists have studied similar problem since the 1950s with considerable new attention in the 1990s, this problem still has no satisfactory solution. Today there exist both descriptive and cognitive models, but the cognitive models still have a long way to go. The models which exist today come from people occupied with traffic flow and from traffic simulations. Previously, such models have only included a very simple model of the driver, but nowadays there are attempts to have a good model of the single driver. Many of the car manufacturers are today working on driver-support systems that handle the longitudinal control of the vehicle. The first European system has just started to sell. In Japan the first system entered the market in 1995, but this system has poor performance and some people count the first European system as the first real ACC system (Adaptive Cruise Controller). Today Daimler-Benz sells an ACC system which works in highway situations and every car manufacturer is also familiar with ACC systems. In fall 1998 a Master Thesis at Volvo resulted in a stop-and-go controller for adaptive cruise controller. All these systems represent an elaboration of the standard cruise control.

Goals

The goal is to achieve a model that describes a human driver's longitudinal behavior of his car related to the car in front. The model should feel comfortable for the driver and represent the behavior in the standard situations. Another goal is to investigate

whether it is possible to explain the model by use of the human physical and cognitive functions.

Research Approach

Many of the models that exist today are static. Therefore, the first approach is to check the presence of dynamics using system identification. The first method that I will use to get a dynamic model is a sub space method. It is also necessary to do literature research on driver behavior and human physiological function, which are significant of the behavior, such as the judgement of distance. In order to get a model of the human driver, it is necessary to collect relevant data an a lot of test cases have to be specified.

Results

The project has just started, and I have been busy with car instrumentation, planning and operation of experiments. System identification studies follow next. As of today, no final results can be presented.

Milestones

During spring and summer 1999, further experiments, data analysis including system identification studies will follow.

External Contacts

The project is done in cooperation with Volvo Technological Development (Div. Driving Support Systems), which supply the test car and their knowledge to the project.

Industries

Volvo Technological Development

Course Work

I have today no course credits. Courses I want to study are: Linear Systems, Control System Design, Cognitive Science

Integrated Control and Scheduling

Anton Cervin

Start of Project	1998-05-01	**Plan**	Lic Tech 2000, PhD 2003
Supervisors	K-E Årzén, B. Bernhardsson	**Course Credits**	39
Publications:	1 conference article		

Research Problem and 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 computers. The first thing to realize is that the performance of digital controllers is subject to the constraints of the computer system. The second thing to realize is that control tasks have special properties and therefore require special scheduling techniques. While a number of sophisticated scheduling techniques exist, such as value-based or flexible scheduling, they have not been specifically developed with control systems in mind. Also, very few papers (if any) have considered a continuous exchange of information between controllers and the scheduler, in order to improve the schedulability and control performance. It remains to develop scheduling techniques, control algorithms, and co-design methods for such systems.

Goals

- Tailor and expand existing fixed-priority scheduling theory to take into account the specific timing needs of control tasks, e.g. by minimizing jitter and delays.
- Create an integrated environment for the design of real-time control systems that includes controller design, scheduling, and worst-case execution time estimation. A first step is to create a simulator where the execution of control tasks is simulated in conjunction with the continuous process dynamics.
- Investigate the scheduling of computing-intensive control algorithms, in particular model predictive control, where an interesting trade-off between sampling periods and the time to search for control signals exists.
- Investigate scheduling and control techniques that achieve higher utilization of the computing resources and better control performance while allowing a few deadlines to be missed.

- Investigate the transient effects of (schedule) mode changes on control performance and derive some timing guarantees and design guidelines.

Research Approach

We intend to combine ideas from scheduling theory and control theory to develop techniques that give better control performance and higher resource utilization. The project is not limited to any specific process models and controllers. As a first step a linear quadratic formulation of the control problem has been considered. We will also look at the scheduling of more computing-intensive controllers, such as model predictive controllers. The project partners at the Department of Computer Science are investigating interactive worst-case execution time analysis, and their results will eventually be incorporated with our results and packaged into a tool. The industrial parters will supply us with case studies at later stages in the project.

The tools used are mainly Matlab and Simulink for both design and evaluation of controllers and schedulers. The real-time kernel at the department is also being doctored for the implementation and experimental evaluation of the techniques.

Results

- An in-depth state-of-the-art survey about integrated control and scheduling has been written [Årzén *et al.*, 1999]. It also contains descriptions of the specific research problems we intend to tackle.
- The scheduling of the different parts of a control algorithms (Calculate Output and Update State) has been investigated [Cervin, 1999].
- A first version of a simulator for real-time and control systems co-design has been developed [Eker and Cervin, 1999].

Milestones

Summer 1999	Complete conference and journal papers about real-time control systems simulator, complete state-of-the-art survey
Fall 1999	Complete conference paper about MPC and scheduling
Spring 2000	Complete Licentiate Thesis
Spring 2003	Complete Doctoral Thesis

External Contacts

During May–July 1998 I visited Lui Sha at the Software Engineering Institute in Pittsburgh, PA, where I learned about rate-monotonic scheduling and got a chance to discuss the project. Since then, Lui Sha has become a professor at the University of Illinois at Urbana Champagne.

Universities

The Department of Computer Science, Lund Institute of Technology

The Software Engineering Institute, Carnegie Mellon University, Pittsburgh, PA, USA

The University of Illinois at Urbana Champagne, IL, USA

Industries

Sigma Exallon AB

DDA Consulting

Course Work

- Right now, I have 39 course credits.
- By the end of the year, I aim to have 54 credits.

Service to the Department

Teaching

I have been a teaching assistant in the following courses:

Course	Last Taught
Automatic Control	Spring 1999
Real-Time Systems	Fall 1998

Initiatives

- Developed Java package for I/O under Windows NT.

Administrative Duties

- Responsible for contacts with the course material print shop KFS AB since August 1998.
- Maintainer of the internal web page *Introduction to the department* since August 1998.

Publications

Cervin, A. (1999): "Improved scheduling of control tasks." In *Proceedings of the 11th Euromicro Conference on Real-Time Systems*, pp. 4–10.

Eker, J. and A. Cervin (1999): "A simulator for real-time and control systems co-design." In *SNART'99 – Konferens om realtidssystem*. To appear.

Årzén, K.-E., B. Bernhardsson, J. Eker, A. Cervin, K. Nilsson, P. Persson, and L. Sha (1999): "Integrated control and scheduling." State-of-the-art survey.

Modelling, Validation and Validity Control

Jonas Eborn

Start of project	1995-01-01	**Plan**	PhD 2000
Supervisor	K. J. Åström, A. Rantzer	**Course Credits**	72 (990608)
Publications:	1 Lic. Thesis, 1 journal article, 10 conf. articles (990601)		

Research Problem and State of the Art

Physical modelling from first principles is a technique that is wide-spread in many engineering domains. Computer support exists but is often limited to one domain, e. g., mechanical systems, and thus difficult to use for control purposes. Building model libraries for general purpose modelling languages/simulators like Modelica™/Dymola is an excellent way of supporting modelling of complex, multi-domain systems. My work aims at providing a model library for thermo-hydraulic systems (thermal power plants, refrigeration systems etc.). Connected to this is also the problem of validating a physical model against measured data. The *model distortion* method based on parameter optimization is a method for validation that is studied.

The simulation tools used today are mainly causal, which means that the user must do a lot of the model manipulation manually and the simulation tool only helps in implementing the model. New object-oriented modelling languages like Modelica and OMOLA allow modelling with a-causal equations, like basic balance equations, but are often hard to use for unexperienced users. Model libraries help overcome this difficulty. Currently, very few methods for validation of physical, non-linear models exist. Visual inspection of plots is often used for qualitative validation, but the only quantitative method found in the literature is the *model distortion* method.

Goals

- 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.

Results

My licentiate thesis [Eborn, 1998b] described the structure and use of the **K2** model library for thermal power plants. Four papers were contained in the thesis, [Eborn and Olsson, 1995; Nilsson and Eborn, 1998; Eborn and Nilsson, 1996; Eborn and Sørlie, 1997].

Since the thesis the basis for a general thermo-hydraulic base library in Modelica™ called HoT-lib has been constructed together with Hubertus and tested in the new Dymola implementation of Modelica. This is described in two papers, [Tummescheit and Eborn, 1998a; Eborn *et al.*, 1999].

Milestones

Summer 1999	Complete reports in Identification and from Boiler case-study.
Fall 1999	Start writing on thesis.
Spring 2000	Finish thesis and defend it ...

During the fall I should also together with guest Falko Wagner from DTU and Hubertus complete HoT-lib and use it to build a model of the Värnamo power plant. It is also important to get a couple of journal articles submitted.

External Contacts

Universities

DTU Lyngby: Falko Jens Wagner, Arne Jakobsen, James Sørlie.

Industries

Sydkraft Konsult AB:	Jan Tuszynski, Jörgen Svensson, Björn Nilsson.
Dynasim AB:	Sven Erik Mattsson, Hilding Elmqvist.
Alfa Laval Thermal AB:	Rolf Christensen, Stefan Burg, Rolf Ekelund.
Danfoss AS:	Njal Pettit, Jakob Fredsted.
Electricité de France:	Damien Faille, Pascale Bendotti.

Course Work

After the spring term 1999 I have completed 72 course points. Including a couple of old courses that need the final touch (project report) the sum of points achieved will be 80. I will complete the course requirement this summer.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
Computer Controlled Systems	Spring 1999
Automatic Control(EFD)	Fall 1998
System Identification	Spring 1998
Process Control	Spring 1996
Automatic Control(M)	Fall 1995

Initiatives

- Lab development on CCS Lab3, Flexible servo
- Captain of the Department Dragon boat team, 1997-99

Administrative Duties

- Responsible for seminar announcements, 1995-99

Master Thesis Supervision

- Niclas Lundqvist, Spring 1999
- Christine Nilsson and Martin Råberg, Fall 1998
- Daniel Übelacker, Fall 1998
- Ola Löfgren and Patrik Svensson, Fall 1997
- Peter Stojnic, Spring 1997
- Jonas Klevhag, Spring 1996

Publications

Åström, K. J., W. Schaufelberger, S. E. Mattsson, and J. Eborn (1996): "COSY workshop, mathematical modeling of complex systems." Report ISRN LUTFD2/TFRT--7551--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Eborn, J. (1994): "Modelling and simulation of an industrial control loop with friction." Master thesis ISRN LUTFD2/TFRT--5501--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Eborn, J. (1998a): "Experiences from using a model database for process modelling." In *Reglermöte'98 Preprints*, pp. 68–72. Lund, Sweden.

Eborn, J. (1998b): *Modelling and Simulation of Thermal Power Plants.* Lic Tech thesis ISRN LUTFD2/TFRT--3219--SE, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Eborn, J. and B. Nilsson (1994): "Object-oriented modelling and simulation of a power plant. Application study in the K2 project." Report ISRN LUTFD2/TFRT--7527--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Eborn, J. and B. Nilsson (1996): "Simulation of a thermal power plant using an object-oriented model database." In *IFAC'96, Preprints 13th World Congress of IFAC*, vol. O, pp. 121–126. San Francisco, California.

Eborn, J. and H. Olsson (1995): "Modelling and simulation of an industrial control loop with friction." In *Proceedings of the 4th IEEE Conference on Control Applications*, pp. 316–322. Albany, New York.

Eborn, J., H. Panagopoulos, and K. J. Åström (1999): "Robust PID control of steam generator water level." In *Proc. of the 14th World Congress, IFAC'99*, vol. G. Beijing, China.

Eborn, J. and J. Sørlie (1997): "Parameter optimization of a non-linear boiler model." In Sydow, Ed., *15th IMACS World Congress*, vol. 5, pp. 725–730. W & T Verlag, Berlin, Germany.

Eborn, J., H. Tummescheit, and K. J. Åström (1999): "Physical system modeling with Modelica." In *Proc. of the 14th World Congress, IFAC'99*, vol. N.

Nilsson, B. and J. Eborn (1994): "K2 model database—Tutorial and reference manual." Report ISRN LUTFD2/TFRT--7528--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Nilsson, B. and J. Eborn (1995): "An object-oriented model database for thermal power plants." In Breitenecker and Husinsky, Eds., *Eurosim '95 Simulation Congress*, pp. 747–752. Elsevier.

Nilsson, B. and J. Eborn (1998): "Object-oriented modelling of thermal power plants." *Mathematical and Computer Modelling of Dynamical Systems*, **4:3**, pp. 207–218.

Nilsson, B., J. Eborn, and S. E. Mattsson (1995): "Omola, OmSim och K2 – en kort kurs," (A short course). Report ISRN LUTFD2/TFRT--7535--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Sørlie, J. and J. Eborn (1997): "A grey-box identification case study: The åström–Bell drum-boiler model." Technical Report ISRN LUTFD2/TFRT--7563--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Sørlie, J. and J. Eborn (1998): "Parameter optimization results for a family of thermo-physical drum boiler models." In *Reglermöte'98 Preprints*, pp. 131–136. Lund, Sweden.

Tummescheit, H. and J. Eborn (1998a): "Design of a thermo-hydraulic model library in Modelica." In Zobel and Moeller, Eds., *Proc. of the 12th European Simulation Multiconference, ESM'98*, pp. 132–136. SCS, Manchester, UK.

Tummescheit, H. and J. Eborn (1998b): "Developing a thermo-hydraulic base library in Modelica." In *Reglermöte'98 Preprints*, pp. 221–225. Lund, Sweden.

Flexible Embedded Systems

Johan Eker

Start of project	1995-10-01	**Plan**	PhD 1999
Supervisor	K. J. Åström and K-E Årzén	**Course Credits**	68
Publications:	1 Lic Thesis, 2 accepted journal articles, 5 conference articles.		

Research Problem and State of the Art

Control design and task scheduling are today in most cases treated as two separate issues. The control community generally assumes that the real-time platform used to implement the control system can provide deterministic, fixed sampling periods as needed. The real-time scheduling community, similarly, assumes that all control algorithms can be modeled as periodic tasks with constant periods, hard deadlines, and known worst case execution times. This simple model has made it possible for the control community to focus on its own problem domain without worrying how scheduling is being done and it has released the scheduling community from the need to understand how scheduling delays impact the stability and performance of the plant under control. From a historical perspective, the separated development of control and scheduling theories for computer based control systems has produced many useful results and served its useful purpose.

Upon closer inspection it is, however, quite clear that neither of the above assumptions need necessarily be true. Our project aims at bridging the gap between the two disciplines. The main idea is to introduce a feedback loop between the control loop and the real-time kernel. Using this approach we believe that more flexible embedded controller may be designed.

Goals

Several parallel issues are currently studied:

- A theoretical approach to design a feedback scheduler.
- Design and development of a simulation environment.
- Design and development of implementation aids, e.g. dedicated languages.

We expect several result to be submitted/published during the summer.

Research Approach

The problem of designing a feedback scheduler is formulated as a recursive optimization. Each control loop is associated with a cost function, that gives control

performance vs sampling rate. The main goal for the feedback scheduler is to adjust the sampling rates so that the sum of all cost functions is minimized, given a desired CPU utilization level.

To evaluate the feedback scheduling strategy a simulation toolbox for MATLAB/Simulink is being developed. A model of a real-time kernel is used for emulating the competing for resources found in a real computer system.

To further test the ideas of feedback scheduling the PÅLSJÖ/PAL system is being extended. A new programming language called Friend is designed. Friend is specifically targeted for supporting implementation of flexible real-time control systems.

Results

A feedback scheduler is designed using LQG and nonlinear optimization theory. The scheduler are to be evaluated using a prototype of our real-time system simulation environment. If everything works out fine we expect to make an implementation.

Milestones

Winter 1999 100%

External Contacts

Universities

Collaborating with Lui Sha, University of Illinois, on feedback scheduling ideas..

Industries

Working Per Påhlsson Diana Control

Course Work

- Now: 68 credits
- Then: 80 credits

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
AK(M)	Spring 1998
AK	Fall 1997
Real Time Systems	Fall 1998
Computer Controlled Systems	Spring 1999

Master Thesis Supervision

- Sabina Brufani, "Manual Control of Unstable Systems", March, 1997.
- Fredrik Emilsson, "Controlling the Ball and Beam Process Using a Video Camera", November, 1997.
- Joakim Kvistholm, "Neural Networks in Extremal Seeking Control", April 1999.

Publications

Eker, J and J. Malmborg. "Design and Implementation of a Hybrid Control Strategy". Accepted for publication in Control Systems Magazine

Eker, J and A. Blomdell. "A Flexible Interactive Environment for Embedded Controllers". Accepted for publication in Control Engineering Practice.

Tona P., J. Eker and M. M'Saad " PALSIMART: A New Framework for Computer Aided Rapid Prototyping of Advanced Control Systems." To be presented at European Control Conference 1999, Karlsruhe, Germany.

Eker, J. "A Tool for Interactive Deveopment of Embedded Control Systems", 14th IFAC World Congress, Beijing, 1999.

Eker J., Mattias Grundelius and Mikael Petersson. "En Dag på Bruket - Studie av Temperaturreglering i Ångflöde." Technical Report TFRT-7580, November 1998, Department of Automatic Control, Lund Institute of Technology

Eker, J. "A Framework for Dynamically Configurable Embedded Controllers", Licentiate Thesis, November 1997, Department of Automatic Control.

Malmborg, J and J. Eker. "Hybrid Control of a Double Tank System", 1997 IEEE International Conference on Control Applications.

Eker, J. and Anders Blomdell. "Patterns in Embedded Control" Technical Report TFRT-7567, December 1997 Department of Automatic Control, Lund Institute of Technology

Eker, J. and K.J. Åström "A Nonlinear Observer for the Inverted Pendelum", Paper, January 1996,1996 IEEE International Conference on Control Applications.

Eker, J. and A. Blomdell "A Structured Interactive Approach to Embedded Control", Paper, July 1996, 4th International Symposium on Intelligent Robotic Systems.

Eker, J. and K.J. Åström "A C++ Class for Polynomial Operations", Technical Report TFRT-7541, December 1995 Department of Automatic Control, Lund Institute of Technology.

Eker, J. and S. Vlachos "Classification of System Dynamics Using Neural Networks", Master Thesis, August 1993, TFRT–5476.

Eker, J. and S. Vlachos "HSLAB - A Program for One-Dimensional Heat Flow Problems.", F.O.A. Report c 20827, December 1990, ISSN 0347–3694.

Motion Control of Open Containers with Slosh Constraints

Mattias Grundelius

Start of project	1996-10-01	**Plan**	PhD 2000
Supervisor	B. Bernhardsson, K. J. Åström	**Course Credits**	59
Publications:	1 Licentiate Thesis, 5 Conference Articles		

Research Problem and State of the Art

The focus in the project has been movement of open packages containing liquid. All packages in the packaging machine follow the same acceleration profile. Between the filling station and the sealing station the package is moved one or several times. The aim is to find the acceleration profile that minimizes the movement time with a maximum allowed slosh.

The method for solving this problem, up till now, has been to use ad-hoc guessing to determine the structure of the acceleration profile. The development engineers use experiments and their experience to tune the parameters.

Goals

Develop systematic methods for calculation and tuning of acceleration profiles.

Research Approach

Derive a model that describes the sloshing phenomena and design methods for parameter estimation. Apply optimal control techniques to calculate the acceleration profile.

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. The results are now being evaluated by the industry.

Milestones

Summer 1999	Plan for PhD work finished
Fall 1999	80% Finished
Summer 2000	Start writing PhD Thesis
Late fall 2000	Defend PhD Thesis

External Contacts

Industries

Tetra Pak Research & Development AB, Lund, Sweden

Tetra Rex Inc., Buffalo Grove, IL

Course Work

Now I have 59 points and at the end of the year I hope I have 80 points.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
AK(FED)	Fall 1998
AK(M)	Spring 1998
Real Time Systems	Fall 1997

Initiatives

Laboratory development in the courses Real-Time systems, Automatic Process Control, Computer-Controlled Systems and Automatic Control Basic Course (FED).

Publications

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.

Grundelius, M. and B. Bernhardsson (1999a): "Control of liquid slosh in an industrial packaging machine." In *Proceedings of the 1999 IEEE International Conference on Control Applications and IEEE International Symposium on Computer Aided Control System Design.* Kohala Coast, Hawaii.

Grundelius, M. and B. Bernhardsson (1999b): "Motion control of open containers with slosh constraints." In *Proceedings of the 14th IFAC World Congress.* Beijing, P.R. China.

Grundelius, M., S. E. Mattsson, and K. J. Åström (1996): "Object-oriented components for simulation of adaptive controllers." In *Proceedings of the 35th IEEE Conference on Decision and Control.* Kobe, Japan.

Åkesson, M., M. Grundelius, and M. Johansson (1996): "New software for the control education in lund." In *Undervisningsdagen Reglermöte'96.* Luleå, Sweden.

Distributed Control Systems in Automotive Applications

Magnus Gäfvert

Start of project	1996-07-25	**Plan**	PhD 2001
Supervisor	B. Wittenmark	**Course Credits**	86
	B. Bernhardsson		
Publications:	3 journal articles, 4 conference articles.		

Research Problem and State of the Art

This work focuses on distributed control in safety critical real-time systems with special application to the automotive industry. It is a joint project with The Mechatronics Department at the Royal Institute of Technoloy, and the Computer Science Department at Chalmers Technical University, within the NUTEK project DICOSMOS.

A relevant problem within this area is to provide a design methodology for these systems such that

- communication effects like random delays and lost samples are handled properly
- specifications are guaranteed to be met at all working conditions
- safe operation can be ensured during failures
- communication channels are utilised efficiently

Distributed safety critical real-time systems are of great importance in the automotive industry. Volvo Technical Development is participating in the project by providing a case study. The case study is to design a yaw and roll stabilisation system for a truck-trailer combination vehicle, by using distributed braking and rear wheel steering. The final result will be an integrated control and communications system of fairly large complexity.

Similar systems are manufactured for passenger cars. Much research effort is spent on this area in many places. The contribution of this project is the focus on methodology, and the integration of communications and control. The actuator combination of individual braking and rear wheel steering is also new to our knowledge.

A side-track of the work is to examine optimal time varying sampling in distributed linear systems with combined LQ cost and communications cost.

Goals

The case study is expected to result in methodologies for designing safety critical real-time integrated communications and control systems.

Research Approach

As a first step a dynamic model of the truck-trailer combination is derived. The model includes yaw and roll dynamics, a sophisticated description of tyre-road contacts using "Magic Formula" models, and simple dynamic models of the braking system pneumatics. The model will be used to derive a control strategy for yaw and roll stabilisation that integrates well with the communication services present in the vehicle. Simulation studies with standardized driving scenarios will be carried out to evaluate the strategies. Methods for analysing integrated communications and control systems will be applied to the system.

Results

Results so far are mainly related to work on friction modelling and compensation [Gäfvert, 1997; Panteley *et al.*, 1997; Olsson *et al.*, 1998; Panteley *et al.*, 1998; Gäfvert, 1998; Gäfvert, 1999; Gäfvert *et al.*, 1999]. A project work within the EU project FAMIMO concerning GDI Engine Control has resulted in the conference submission [Gäfvert *et al.*, 2000].

Milestones

Summer 1999	first paper on the DICOSMOS case study
Spring 2000	80% finished
Spring 2001	Grand Final ...

External Contacts

The DICOSMOS project has Volvo Technical Development as industrial partner. I spend approximately 1 week per month at VTD in Göteborg. I also spend time at the other participating universities: the Royal Institute of Technology and Chalmers Technical University.

Siemens Automotive is participating in the FAMIMO project. I have presented results to Siemens Automotive at a visit in Toulouse, France.

Universities

Chalmers Technical University

Royal Institute of Technology

Industries

Volvo Technical Development

Siemens Automotive

Course Work

I have fulfilled the course requirements of the Ph.D. with 86 points.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
Computer Controlled Systems	Spring 1999
Real-time Systems	Fall 1998
BEST Summer School	Summer 1998
Computer Controlled Systems	Spring 1998
Real-time Systems	Fall 1997
Basic Course (M)	Spring 1997
Basic Course (FED)	Fall 1996

Initiatives

Participated in the development of the interactive learning tools for control: *ICTools* [Zackrisson, 1997; Johansson *et al.*, 1998].

Participated in the reorganization of the laboratory exercises in Computer Controlled Systems to Linux with Matlab/Simulink with real-time enhancements.

Publications

Andersson, L., M. Gäfvert, S. Hedlund, and C. Johansson (1998): "Industrial case studies in control — the crude alcohol distillery in nöbbelöv." Technical Report ISRN LUTFD2/TFRT--ISRN LUTFD2/TFRT–7573–SE--SE. Dept. of Automatic Control, Lund Institute of Technology.

Gäfvert, M. (1997): "Comparisons of two dynamic friction models." In *Proc. Sixth IEEE Conference on Control Applications*, pp. 386–391. Hartford, USA.

Gäfvert, M. (1998): "Modelling the furuta pendulum." Technical Report ISRN LUTFD2/TFRT--ISRN LUTFD2/TFRT–7574–SE--SE. Dept. of Automatic Control, Lund Institute of Technology.

Gäfvert, M. (1999): "Dynamic model based friction compensation on the furuta pendulum." In *Proc. 1999 IEEE International Conference on Control Applications*. Hawaii.

Gäfvert, M., L. M. Pedersen, and K.-E. Årzén (2000): "Simple feedback control and mode switching strategies for gdi engines." In *Proceeding of 2000 SAE International Congress & Exposition*. Detroit. Submitted.

Gäfvert, M., J. Svensson, and K. J. Åström (1999): "Friction and friction compensation in the furuta pendulum." In *Proc. European Control Conference ECC'99*. Karlsruhe.

Johansson, M., K. J. Åström, and M. Gäfvert (1998): "Interactive tools for education in automatic control." *IEEE Control Systems Magazine*, **18:3**, pp. 33–40.

Olsson, H., K. J. Åström, C. Canudas de Wit, M. Gäfvert, and P. Lischinsky (1998): "Friction models and friction compensation." *European Journal of Control*, **1998:4**, pp. 176–195.

Panteley, E., R. Ortega, and M. Gäfvert (1997): "An adaptive friction compensator for global tracking in robot manipulators." In *Proc. SYROCO'97, 5th IFAC Symposium on Robot Control*. Nantes.

Panteley, E., R. Ortega, and M. Gäfvert (1998): "An adaptive friction compensator for global tracking in robot manipulators." *Systems & Control Letters*, **33:5**, pp. 307–313.

Zackrisson, M. (1997): "Matteprogram får eleverna att förstå tekniken." *Ny Teknik*, **No 48**.

Optimal Control of Hybrid Systems

Sven Hedlund

Start of project	1997-09-01	**Plan**	PhD 2002
Supervisor	A. Rantzer, K-E Årzén	**Course Credits**	40
Publications:	2 Conference Articles.		

Research Problem and State of the Art

Hybrid systems are systems that involve interaction between discrete and continuous dynamics. Modeling and simulation of a system often require a combination of mathematical models from a variety of engineering disciplines. The structure of such submodels can be very different, some can be discrete and some continuous.

Practical control systems typically involve switching between several different modes, depending on the range of operation. The fundamental problem with these systems is their complex mixture of discrete and continuous variables; even if the dynamics in each mode is simple and well understood, automatic mode switching can give rise to unexpected phenomena. The current lack of analysis methods compels control designers to rely on simulations.

Goal

The goal of this project is to develop analysis and synthesis methods for hybrid systems.

The current research focuses on discretization of a hybrid version of the Hamilton-Jacobi-Bellman inequality, turning the optimal control problem into a linear program. The main result so far is a lower bound on the Cost to go-function and many issues remain to be investigated. General questions that need to be addressed are

- how should the discretization be made not to loose the properties of the original problem?
- what information could be extracted from the dual variables of the LP solution?
- how should one get a control signal from the discretized cost function?

Having explored the above items, the resulting theory could be used to get methods for

- switching strategies. Given a set of continuous dynamic systems, how should one switch optimally between them?
- initialization of the continuous states in controllers to get bumpless switching.

Whatever direction the research takes, the resulting methods should be tested on several examples — school examples to examine the performance on well known problems, as well as problems in industry to verify practicability.

Research Approach

The current approach is to approximate and reformulate partly continuous problems into linear programming.

Results

There are few results from the current research so far [Hedlund and Rantzer, 1999]. I have previously worked with Mikael Johansson, developing a MATLAB toolbox for analysis and synthesis of piecewise linear systems [Hedlund and Johansson, 1999b; Hedlund and Johansson, 1999a]. The toolbox is mainly based on LMI computations.

Milestones

Fall 1999	Lic Tech Thesis
Fall 1999	Write one journal article
Fall 2001	80%
Fall 2002	PhD Thesis

External Contacts

During summer 1999, I visited the Department of Control Systems Engineering at Tokyo Institute of Technology, where I worked with Prof. Tetsuya Iwasaki. I also visited some other universities during my stay in Tokyo.

Part of my work has been financed by the EU research project FAMIMO, Fuzzy Algorithms for MIMO systems. FAMIMO aims at designing fuzzy systems for reliable control of complex processes. The partners develop their control methods and test them on two multivariable nonlinear benchmarks with strong industrial relevance. In addition to the academic partners (in Belgium, France, the Netherlands, and Spain), Siemens Automotive is involved providing the major benchmark.

I am currently working in a project called H^2C, Heterogeneous Hybrid Control. The key objective is to develop innovative theory and algorithms for heterogeneous and hybrid control, including low-level control design, high-level switching and blending strategies, and an overall stability and robustness analysis. The

theory should also result in software tools that can be used for further consolidation. The H^2C consortium has two industrial partners, Daimler-Benz that will provide a test vehicle and SINTEF.

Course Work

I have acquired 40 credit points so far and I aim for another 10 credits at the end of this year.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
Nonlinear Control and Servo Systems	Spring 1999
Real Time Systems	Fall 1998
BEST Summer School	Summer 1998
Computer-Controlled Systems	Spring 1998
Automatic Control, Basic Course	Fall 1997

Initiatives

I have helped developing exercises and labs for the course in nonlinear control.

During summer 1998, I developed exercises for "Dynamics and Control", a BEST summer course.

Administrative Duties

Since 1999, I am responsible for the documentation of written exams.

I organized the graduate student's day at the Swedish control meeting 1998, together with Hélène Panagopoulos.

Publications

Andersson, L., M. Gäfvert, S. Hedlund, and C. Johansson (1998): "Industrial case studies in control — the crude alcohol distillery in nöbbelöv." Technical Report ISRN LUTFD2/TFRT--ISRN LUTFD2/TFRT–7573–SE--SE. Dept. of Automatic Control, Lund Institute of Technology.

Arzen, K.-E., M. Johansson, S. Hedlund, J. Malmborg, A. Rantzer, and B. Bernhardsson (1998): "Fuzzy heterogeneous control." Technical Report. Department of Automatic Control.

Hedlund, S. and M. Johansson (1999a): "PWLTool — A Matlab toolbox for analysis of piecewise linear systems." Report TFRT-7582. Department of Automatic Control, Lund Institute of Technology, Lund,Sweden.

Hedlund, S. and M. Johansson (1999b): "A toolbox for computational analysis of piecewise linear systems." In *Proceedings of European Control Conference.* Karlsruhe.

Hedlund, S. and A. Rantzer (1999): "Optimal control of hybrid systems." In *IEEE Conference on Decision and Control.* Phoenix. In submission.

Basic control functions for the process industry

Ari Ingimundarson

Start of project	1999-February	**Plan**	Lic 2000
Supervisor	T. Hägglund	**Course Credits**	19

Research Problem and State of the Art

The aim of this project is to improve basic control functions used in the process industry and to develop new control functions. As a first step, problems related to processes with long dead-times will be investigated. These processes are frequently reported as problematic in the process industry. The goal is to develop automatic tuning functions for dead-time compensating controllers as well as detection procedures for these processes.

Goals

First sub-project: Automatic tuning of dead-time compensating controllers

- Controller tuning is regarded as difficult for processes with long dead-time. The goal is to develop simple and self reliant identification methods that will give information that can be used for controller structure selection and controller tuning.

Research Approach

A new method has been suggested that fulfills the requirements of simplicity and self reliance. By simulation (Simulink) the method has been investigated and compared with existing methods.

Results

- A novel approach with many of the above mentioned qualities has been derived, tested and compared with existing methods.
- Industrial relevance confirmed through collaboration with ABB.

Milestones

Summer 1999	First sub-project documented and paper written
Fall 1999	New sub-project started

External Contacts

Industries

ABB Automation - Active collaboration

Course Work

- 1999-06-03 I had 19 credits in finished courses. I have 12 credits in courses that I have finished but they have not been counted in yet.
- I hope to have at least 45 points in the end of the year.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
Automatic Process Control (K)	Spring 1999

Finding a good PhD project

Bo Lincoln

Start of project	1999	**Plan**	PhD 2003
Supervisor	B. Bernhardsson	**Course Credits**	≈ 22

Research Problem and State of the Art

No specific problem yet, except for trying to find a project. Interested in the use of wireless networks in control. I have also been following the work of the robot group.

Small projects: In the System identification class I made a little pendubot experiment with the IRB2000 robot. I've been working on modeling of a two-Furuta-pendulum-project, and design of a controller. Hopefully the real process will be tested.

Milestones

Summer 1999	Specify research project, do some practical project on control.
Fall 1999	Courses and teaching. Literature study for PhD project.

Course Work

This spring I studied: "System Identification" (MSc Course), "Nonlinear Control" (MSc Course), "Linear Systems", "Optimization in an Engineering Context", "Optimal Control", and "Computer Vision" (Maths@LTH).

- I have ≈ 22 credits right now.
- At the end of this year I will have about 40 credits.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
AK(M)	Spring 1999

Initiatives

- Handled the purchase of sound equipment for the new seminar room.

Analysis of Power Quality in Distribution Networks and Loads

Erik Möllerstedt

Start of project	1995-07-01	**Plan**	PhD 2000
Supervisors	B. Bernhardsson	**Course Credits**	65
	A. Rantzer		
Publications:	1 licentiate thesis (April 98), 6 conference articles,		
	2 technical reports		

Research Problem and State of the Art

In electrical networks, more and more switching power electronics is used. Analysis of such systems is extremely complicated. Often one has to rely on simulations, which is very time consuming for large network with a lot of switching devices.

The aim of the project is to derive simple representations for networks with nonlinear and switching components. These should equivalently describe the behaviour of the networks close to nominal operating conditions, and thus simplify analysis and simulation. Of special interest is the amount of harmonic distortion in periodic systems. For switching components, there is coupling between different frequencies, which means that energy can be transfered from one frequency to another. This means that traditional linear analysis does not apply.

In the licentiate work, I derived a model structure for steady state analysis. The models are called Harmonic Norton Equivalents (HNEs). Like the well known Norton Equivalent for linear networks, the HNE equivalently describes the behaviour of a whole network, and can be obtained experimentally. The HNE is a linearization of the system around the nominal sinusoidal voltage. This gives a linear time periodic (LTP) system.

The recent work focuses on how the structure can be used for stability and robustness analysis. Is there a stable periodic solution, and if so, how close to instability are we?

Goals

- Derive stability results for LTP systems.
- Show that LTP systems are suitable for small signal stability analysis of power networks with switching components.
- Results for train application in collaboration with Adtranz.

- PhD summer 2000

Research Approach

Power electronic devices are time varying processes, excited by a periodic signal, the applied voltage. Linearizing around the periodic excitation results in linear time periodic (LTP-) systems. This class of systems is of interest also for other applications with periodic excitation, for instance vibrations of helicopter rotors, and sampling of continuous signals.

We intend to develop a stability theory for LTP systems based on the theory for linear systems. Stability results should be based on Harmonic Norton Equivalents, a steady-state model structure for LTP systems which was developed in the licenciate work.

We will apply the theory on a simple system consisting of two trains, with switching dynamics, overhead power lines, and a substation. The system was proposed by Adtranz, who are very interested in our work.

Results

My licentiate thesis [Möllerstedt, 1998] is based on two conference papers [Möllerstedt *et al.*, 1997c; Möllerstedt *et al.*, 1997] and two technical reports [Möllerstedt *et al.*, 1997a; Möllerstedt *et al.*, 1997b]. 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.

Recent work has focused on possibilities to use the Harmonic Norton Equivalents for stability analysis. This has lead to the work on LTP systems. We have shown that the Harmonic Norton Equivalent can be interpreted as the frequency response for a LTP system, and results like the Nyquist theorem are easily generalized.

Milestones

Spring 1999	write 2 journal articles
Summer 1999	get my second child
Fall 1999	joint article with Adtranz
Spring 2000	PhD thesis

External Contacts

My project is sponsored by **Elforsk AB** within the Electra program. In the reference group there are representatives from Sydkraft AB, Vattenfall AB, and ABB Power Systems. Also in the reference group is Lennart Söder at Dept. of

Electric Power Engineering, KTH. He is supervising a PhD student in a closely related area.

Adtranz, Zürich, and **ABB Corporate Research in Baden-Dätwill** are very interested in our work, and are incorporating the methods in a software tool for analysis of distribution networks for trains. They have supported us with a model, and we are working on a joint publication. We also have a master's student, Henrik Sandberg, who is using our methods to model trains at ABB.

Universities

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

Industries

- Sydkraft AB: Gunnar Ridell
- Vattenfall AB: Anders Åberg
- ABB Power Systems: Bernt Bergdahl
- Adtranz: Marcus Meyer
- ABB Corporate Research: Andrew Paice
- Daimler-Chrysler: Joachim Böcker, Sebastian Scheffler

Course Work

I have 65 credits of course work today (990610), and will hopefully have the full 80 by the end of this year.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
Nonlinear Control	Spring 1999
AK(FED)	Fall 1998
Adaptive Control	Fall 1997
Computer Controlled Systems	Spring 1997
Process Control	Spring 1995

Initiatives

- Initiated a video about Automatic Control and the courses we offer. The goal was to attract and motivate students.
- Helped to develop lectures, exercises, and labs for the course in nonlinear control

Master Thesis Supervision

- I have supervised the project *Autofocus and Control of a Hematology Instrument* by Magnus Pettersson at Cellavision AB.
- I have 2 ongoing master thesis projects in cooperation with Daimler-Chrysler and ABB/Adtranz.

Publications

Åkesson, M., E. Gustafson, and K. H. Johansson (1996): "Control design for a helicopter lab process." In *IFAC'96, Preprints 13th World Congress of IFAC.* San Francisco, California.

Gustafson, E., A. Åberg, and K. J. Åström (1995): "Subsynchronous resonance, a controller for active damping." In *Proceedings of 4th IEEE Conference on Control Applications*, pp. 389–394. Albany, New York.

Möllerstedt, E., B. Bernhardsson, and S. E. Mattsson (1997): "A simple model for harmonics in electrical distribution networks." In *Proceedings of the 36th IEEE Conference on Decision and Control.* San Diego, California.

Möllerstedt, E., B. Bernhardsson, and S. E. Mattsson (1999): "A load model for analysis and control of electric distribution networks." In *To be presented at IFAC World Congress 1999, Beijing, China.*

Möllerstedt, E., S. E. Mattsson, and B. Bernhardsson (1997a): "Modeling of electricity distribution network and components." report ISRN LUTFD2/TFRT--7557--SE. Department of Automatic Control, Lund.

Möllerstedt, E., S. E. Mattsson, and B. Bernhardsson (1997b): "Modeling of electricity distribution network and components – status report 1997-11-30." report ISRN LUTFD2/TFRT--7570--SE. Department of Automatic Control, Lund.

Möllerstedt, E., S. E. Mattsson, and B. Bernhardsson (1997c): "A new approach to steady-state analysis of power distribution networks." In Sydow, Ed., *15th IMACS World Congress*, vol. 5, pp. 677–682. W & T Verlag, Berlin, Germany.

Möllerstedt, E., S. E. Mattsson, and B. Bernhardsson (1998): "A new approach to steady-state analysis of power distribution networks." In *Preprints Reglermöte '98*, pp. 269–274. Dept of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Möllerstedt, E. (1998): *An Aggregated Approach to Harmonic Modelling of Loads in Power Distribution Networks.* Lic Tech thesis ISRN LUTFD2/TFRT--3221--SE, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

PID Control

Hélène Panagopoulos

Start of project	1996-01-31	**Plan**	PhD 2000
Supervisor	K. J. Åström, T. Hägglund.	**Course Credits**	66
Publications:	1 Lic thesis, 1 journal articles, 4 conference articles.		

Research Problem and State of the Art

PID control is by far the most common control algorithm and very much has been written about it. 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.

Goals

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 oscillatory systems. My ambition is to investigate these kind of systems and try to find a systematic way to insert and design a filter such that the effects of a load disturbance on the output is eliminated.

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 and compensation for oscillatory systems.

Research Approach

My near term goal is to investigate what information about the process is required for design of PID controllers and too develop methods to derive this information from plant experiments. To use the PID design on practical applications. Furthermore, I will investigate schemes for control of oscillatory systems. Hopefully, this will end up into a thesis at the end of this year.

Results

Until today an efficient numerical method for designing PI and PID controllers has been derived. 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 have been developed. The results for the design of PI controllers have been documented in the conference paper [Panagopoulos *et al.*, 1997] and in the full paper [Åström *et al.*, 1998]. The result for the PID controller design has been documented in [Panagopoulos *et al.*, 1999] and [Panagopoulos, 1998]. It has also been shown how PID control design and $\mathcal{H}_\infty$ loop shaping design are related, see [Panagopoulos and Åström, 1998] and [Panagopoulos, 1998].

An internal report has also been written, see [Panagopoulos *et al.*, 1997], which gives a thorough analysis of the Lambda method.

Milestones

- Requirements needed to determine if PI or PID control is suitable, from knowledge of the process.
- Oscillative systems.
- Practical Implementation.
- Introduction.

External Contacts

In my project I have been in contact with Swedish industrial partners as Skogsindustrierenas Tekniska AB, ModoPaper in Husum, Assi Domän in Frövi, ABB and with universities as Rensselaer Polytechnique Institute and University of California Santa Barbara in the US. These contacts have given me good insights into my project and valuable contacts.

Beside 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.*, 1997].

During the 25th until the 27th of January, 1999 I visited MoDo's pulp and paper factory in Husum, Sweden for testing my design methods for PI and PID controllers. This visit has resulted into a pursued cooperation with the factory in testing my design methods and a conference article together with another graduate student, Anders Wallén, at the department.

Course Work

At this moment I have 66 course credits which I hope will be 80 at the end of this year.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
System Identification	Spring 1999
Adaptive Control	Fall 1998
Computer Controlled Systems	Spring 1998
AK(M)	Spring 1998
AK(EFD)	Fall 1996
AK(M)	Spring 1996
AK(EFD)	Fall 1995

Initiatives

I have achieved to obtain several grants which have financed my visits to other universities, workshops and conferences. I have also been involved in the course development of the undergraduate course in System Identification.

Administrative Duties

During 1996-1998 I have been responsible for the course literature. For the Swedish control meeting 1998 I was in in charge, together with the graduate student Sven Hedlund, of organizing the graduate students day. In 1998 I was in charge of the research abstracts of the department's graduate students.

Publications

Åström, K. J., H. Panagopoulos, and T. Hägglund (1998): "Design of PI controllers based on non-convex optimization." *Automatica*, **35:5**.

Panagopoulos, H. (1998): *PID Controller Design*. Lic Tech thesis ISRN LUTFD2/TFRT--3224--SE, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Panagopoulos, H. and K. J. Åström (1998): "PID control design and $\mathcal{H}_\infty$ loop shaping." In Proceedings of the 1999 International Conference on Control Applications, Hawaii, USA, August 23-26, 1999. Accepted for presentation.

Panagopoulos, H., K. J. Åström, and T. Hägglund (1997): "Design of PI controllers." In *Proc. 1997 IEEE International Conference on Control Applications*, pp. 417–422. Hartford, Connecticut.

Panagopoulos, H., K. J. Åström, and T. Hägglund (1999): "Design of PID controllers based on constrained optimization." In *1999 American Control Conference*. San Diego, California.

Panagopoulos, H., T. Hägglund, and K. J. Åström (1997): "The Lambda method for tuning PI controllers." Report ISRN LUTFD2/TFRT--7564--SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Industrial Aspects of On-line Monitoring and Diagnosis

Mikael Petersson

Start of project	1998-01-01	**Plan**	Lic 2k, PhD 2002
Supervisors	K-E Årzén	& T. Hägglund	
Publications:	None	**Course Credits**	30

Research Problem and State of the Art

The process industry of today is highly automated. The control loops outnumber the number of operators and maintenance people. The processes to control are getting more complex. With this in mind, it would be desirable to have a tool for analyzing control loops. The goals are to determine whether the loops are well tuned, to verify if an appropriate control strategy has been chosen, and, when not, to get a measure on how much better control is achievable using another control strategy.

The project concerns monitoring and auditing simple control loops. As a start, SISO loops with an extra measurable signal are considered. The first step is to establish the relation between the control loop and the extra signal, then how to use this signal to achieve better control. Finally, a measure on how much better control can be obtained is desirable; preferably weighted with the complexity of the control strategy chosen.

Goals

- Develop systematic methods for selection of control strategies for a process section.
- Establish properties of different disturbances on feedback loops.
- Performance monitoring of MIMO systems.

Research Approach

A survey of control strategies and structures will give insight in the fundamental properties of the systems in consideration. Initially a basic system is investigated. It consists of a simple feedback loop with first or second order process. The effects of different types of disturbances are studied. Further on, systems that can be found in the pulp and paper industry will be subject for the project.

The tool-set used consists so far of simple methods such as looking for patterns in the signals, statistic correlation, minimum variance, and identification. The computer tools used are Matlab, and Simulink.

The industrial partner provides real process knowledge and data, and furthermore real experiments can be performed. Currently a data logging device is installed at a paper mill in Sweden which records data batches at least twice a day.

Results

- Literature study on diagnostics
- Study of on-line change detection methods
- Literature study of control performance assessment

Milestones

Summer 1999	Overview over different control structures and strategies.
Fall 2000	Licentiate thesis
Spring 2002	Start writing my PhD thesis
End of 2002	PhD thesis ... end of project

External Contacts

The major industrial partner in this project is ABB Corporate Research where I am employed. Cooperation with other ABB companies, partners, and the pulp and paper industry will take place during the project.

During the spring 1999, I attended a COSY course on Fault Tolerant Methods in Control and Automation. The course was organized by the department of Control Engineering at Aalborg University.

This spring, my related work at ABB has resulted in visits to LiTH and KTH.

Universities

AUC Aalborg University, Dept. of Control Engineering, Denmark

LiU Linköping University, ISY, Automatic Control: Lennart Ljung, Urban Forsell, and Fredrik Gustafsson.

KTH Royal Institute of Technology, S^3, Process Control: Alf Isaksson, and Alexander Horch.

Industries

ABB ABB Corporate Research, Sweden

AssiDomän AssiDomän Corporate R & D, Sweden: Stefan Rönnbäck

Course Work

- Course credits today: 30
- Course credits by end of year (estimated): 42

Service to the Department

This section does not apply to me as an industrial PhD student. I have however volunteered to participate in some education related to my field of research.

Teaching

I have been teaching assistant in the following course

Course	Last Taught
System Identification	Spring 1999

Initiatives

During spring the assistants of System Identification conducted major course development in cooperation with the research engineers:

- Laboratory exercises has been transferred to Linux/Simulink-environment, and
- the Pendubot has been made available as a laboratory process.

Nonlinear Control and Robotics

Anders Robertsson

Start of project	1993-10-01	**Plan**	PhD 1999
Supervisor	R. Johansson	**Course Credits**	85
Publications:	2 journal articles, 1 book chapter, 10 conference articles.		

Research Problem and 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 and tracking control, there are many open issues. In contrast to the linear case, the certainty equivalence property does not 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, though still much remains to be done for the output feedback case.

Goals

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 algorithms based on nonlinear state feedback in combination with observers, and under what limitations?".

Some control principles, like "exact linearization" (also called "computed torque"), have exhibited very poor robustness properties, whereas passivity based control can be assumed to have better behavior with respect to robustness and stability when used together with observers.

Research Approach

We use nonlinear theory for (model based) observer design and stabilization : Passivity-based control, Input-to-State Stability, Cascaded Systems, and Lyapunov techniques, e.g., backstepping.

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.

Results

During 1993-1996, 1996-1999 I have worked in the NUTEK project *Lund Research Programme in Autonomous Robotics*, (RAS), which resulted in the Open Robot Control System, [Nilsson *et al.*, 1994], and a "demonstrator" for using off-line programming tools for real-time control of robots in an arc-welding process. The project has also brought us to an integration of resources from the Dept. of Automatic Control, Dept. of Industrial Electrical Engineering and Automation, and the Dept. of Production and Materials Engineering. System identification experiments for controller tuning in the Robotics lab are addressed in [Johansson *et al.*, 1997], [Johansson *et al.*, 1998a].
Other results are

- A nonlinear ship-model with resemblance to robot dynamics has been studied for observer design and control, [Robertsson and Johansson, 1998a], [Robertsson and Johansson, 1997], [Robertsson and Johansson, 1998b] .
- Semi-global output-feedback results for robot control.
- Extensions of passivity results, [Johansson and Robertsson, 1999].
- Observer-backstepping for a class of nonminimum-phase systems, [Robertsson and Johansson, 1999b], [Robertsson and Johansson, 1999a].
- Output Feedback Tracking of Nonholonomic Systems in Chained Form, [Lefeber *et al.*, 1999a], [Lefeber *et al.*, 1999b].
- Robot control and identification [Valera *et al.*, 1999], [Johansson *et al.*, 1998a].

Experiments to be done:

- Evaluation of observer-based position control on an industrial robot.
- Experiments and evaluation of force control schemes.

Milestones

Fall 99 PhD

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, visited Lund, [Lefeber *et al.*, 1999a], [Lefeber *et al.*, 1999b]. Angel Valera, Valencia and Norberto Pires, Coimbra, have visited the Robotics Lab during 1998-99 for longer stays and will be back again for continued cooperation.

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

Universities

TU Twente, the Netherlands

University of Coimbra, Portugal

University of Valencia, Spain

Industries

ABB Robotics, Västerås

ABB Corporate Research, Västerås

Course Work

85 points

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
AK EFD	1998
AK M	1998
Adaptive Control	1997
Nonlinear Control	1996
Computer Controlled Systems	1994

Initiatives

- Lab development in Adaptive control, Nonlinear control, and System identification
- 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.

Master Thesis Supervision

I have participated as advisor in the following Master Thesis projects

- Michele Gianino, 1994
- Jonas Sonnerfeldt, 1995
- Jan Peter Meeuwse, 1995
- Bart Hendriks, 1996
- Martin Rentsch, 1998
- Johan Bengtsson and Anders Ahlstrand, 1999

and I have supervised numerous student projects related to the Robotics Lab.

Publications

Johansson, R. and A. Robertsson (1998): "Stability analysis of adaptive output feedback systems." In *Proc of the 37th IEEE Conf. Decision and Control*, pp. 4008–4009.

Johansson, R. and A. Robertsson (1999): "The yakubovich-kalman-popov lemma and stability analysis of dynamic output feedback systems." In *Proceedings of IFAC'99*. Beijing, China.

Johansson, R., A. Robertsson, K. Nilsson, and M. Verhaegen (1997): "State-space system identification of robot manipulator dynamics." In *Proceedings of "SNART-97"*, pp. 152–158. Lund, Sweden.

Johansson, R., A. Robertsson, K. Nilsson, and M. Verhaegen (1998a): "State-space system identification of robot manipulator dynamics." *Mechatronics*. (accepted).

Johansson, R., M. Verhaegen, C. T. Chou, and A. Robertsson (1998b): "Behavioral model identification." In *Proc of the 37th IEEE Conf. Decision and Control*, pp. 126–131. Tampa, Florida.

Lefeber, E., A. Robertsson, and H. Nijmeijer (1999a): "Output feedback tracking of nonholonomic systems in chained form." accepted, the European Control Conference-1999.

Lefeber, E., A. Robertsson, and H. Nijmeijer (1999b): "Output feedback tracking of nonholonomic systems in chained form." In *18th Benelux meeting on System and Control*. Houthalen-Helchteren, Begium.

Nilsson, K., A. Robertsson, and R. Johansson (1994): "Robot control research in lund." In *Preprints, Reglermöte'94*, pp. 1–6. Västerås, Sweden.

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

Robertsson, A. and R. Johansson (1998a): "Comments on 'Nonlinear output feedback control of dynamically positioned ships using vectorial observer backstepping'." *IEEE Transactions on Control Systems Technology*, **6:3**, pp. 439–441.

Robertsson, A. and R. Johansson (1998b): "Nonlinear observers and output feedback control with application to dynamically positioned ships." In *4th IFAC Nonlinear Control Systems Design Symposium (NOLCOS'98)*. Enschede, Netherlands.

Robertsson, A. and R. Johansson (1999a): "Observer backstepping for a class of nonminimum-phase systems." *submitted to IEEE Transactions on Automatic Control*.

Robertsson, A. and R. Johansson (1999b): "Observer backstepping for nonminimum-phase systems." In *IEEE Conf. Decision and Control (CDC'99); (submitted to review)*.

Valera, A., A. Robertsson, K. Nilsson, and R. Johansson (1999): "Interactive on-line evalutaion of robot motion control." In *Proceedings of IEEE CCA-99*. Hawaii.

Modeling of Thermo-Hydraulics

Hubertus Tummescheit

Start of project:	1996-04-15	**Plan:**	PhD 2001
Supervisor:	K. J. Åström, A. Rantzer	**Course credits:**	61
Publications:	1 journal article, 6 conference articles		

Research Problem and State of the Art

Object oriented modeling has been a research topic in Lund for a long time: Dymola, Omola, the K2 libraries and finally the Modelica language effort. Object oriented modeling libraries have quite a success in mechatronics, but they are not used much in thermodynamics. Two main reasons for that are the lack of reusable medium property routines and a lack of robust models. Our industrial partners have expressed interest in physical models for their application domains, but earlier models mainly lacked "robustness" for industrial day-to-day use. This also calls for better integration between control engineering tools and design tools. With the ongoing development of the Modelica language (syntax extensions to PDE, standardized API for simulation) these problems can be addressed quite well. The Modelica language also offers new possibilities to use different classes of physical models as class parameters to the same plant model. For thermo hydraulic and process engineering models this offers a new level of model reuse.

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)

1. are usually only for a specific application domain (APROS, Sinda/Fluint, TRANSYS),
2. lack interfaces for interaction with other software,
3. are 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.

Goals

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. The models should fulfill two main requirements:

- be *reusable* for many applications,
- be *robust*, i. e. work even with incomplete knowledge about boundary and initial conditions and certain parameters.

The generic model constructs of the modeling language Modelica are extensively used to implement the library.

Research Approach

Within the development of the Modelica language my main interests are

- language constructs for generic models,
- modeling of distributed processes and PDE,
- interfacing to external code and databases.

The current results and the ongoing development of the Modelica language are then used and tested with the thermo-hydraulic library design.

- Main items of the current work are:
  - design a library structure
  - implement the physical base models
  - validate them in industry projects
- The main tools are:
  - Physical modeling
  - Object oriented design techniques
  - Modelica language, Dymola
  - Computer algebra tools: Mathematica and Maple

Results

- Implemented efficient steam-tables and refrigerant properties for dynamic simulation.
- Developed and enhanced different type of models for two phase flow for the Modelica HotLib/CoolLib Libraries.

Milestones

Summer 1999	Finish main part of model implementation.
Fall 1999	Library structuring together with Falko Wagner
Spring 2000	journal article on results (part of thesis)

External Contacts

Universities

DTU Lyngby:	Falko Jens Wagner, Arne Jakobsen.
Linköping TH:	Peter Fritzsson, Henrik Nilsson.
TU Hamburg Harburg	Gerhard Schmitz, Ole Engel.
TU Berlin	Stefan Jähnichen.

Industries

Dynasim AB:	Sven Erik Mattsson, Hilding Elmqvist.
Sydkraft Konsult AB:	Jan Tuszynski, Jörgen Svensson.
Danfoss AS:	Njal Pettit, Jakob Fredsted.

Course Work

After the spring term 1999 I have completed 61 course points. After the fall term I plan to have completed 71.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
AK(M)	Spring 1999
AK(FED)	Fall 1998

Administrative Duties

- Taking care of the Modelica design group web-site.

Master Thesis Supervision

- Olaf Bauer, Spring 1999.

Publications

Eborn, J., H. Tummescheit, and K. J. Åström (1999): "Physical system modeling with Modelica." In *Proc. of the 14th World Congress, IFAC'99*, vol. N.

Hahn, W. and A. Lehmann, Eds. (1997): *Proceedings of the 9th European Simulation Symposium ESS97*, Budapest, Hungary. Society for Computer Simulation International.

Sydow, A., Ed. (1997): *Proceedings of the 15th IMACS world congress on Scientific Computation, Modelling and Applied Mathematics*, vol. 6, Berlin, Germany. Wissenschaft und Technik Verlag.

Tummescheit, H. (1999): "Objektorientierte modellierung thermohydraulischer systeme." *To appear in: Automatisierungstechnik.*

Tummescheit, H. and J. Eborn (1998a): "Design of a thermo-hydraulic model library in Modelica." In Zobel and Moeller, Eds., *Proc. of the 12th European Simulation Multiconference, ESM'98*, pp. 132–136. SCS, Manchester, UK.

Tummescheit, H. and J. Eborn (1998b): "Developing a thermo-hydraulic base library in Modelica." In *Preprints of Reglermöte '98*, pp. 221–225. Lund Institute of Technology, Sweden.

Tummescheit, H., M. Klose, and T. Ernst (1997): "Modelica and smile – a case study applying object-oriented concepts to multi-facet modeling." In Hahn and Lehmann, Eds., *Simulation in Industry*, pp. 122–126. Society for Computer Simulation International, Budapest, Hungary.

Tummescheit, H. and R. Pitz-Paal (1997): "Simulation of a solar thermal central receiver power plant." In Sydow, Ed., *Proceedings of the 15th IMACS world congress on Scientific Computation, Modelling and Applied Mathematics*, vol. 6, pp. 671–676. Wissenschaft und Technik Verlag, Berlin, Germany.

Autonomous Control

Anders Wallén

Start of project	1991-10-01	**Plan**	PhD 1999
Supervisors	K. J. Åström, T. Hägglund	**Course Credits**	80+
Publications:	1 book chapter, 6 conference articles.		

Research Problem and 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 no or very little support for this.

Goals

The main goal is 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. Specific subgoals are:

- Present suitable implementation structures.
- Show how Grafchart can be used to implement the controller logic. Examples with loop assessment experiments and auto-tuner.
- Present an interactive modeling tool.
- Present a method for fast set point response.

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 in this platform.

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 [Wallén, 1997]. It has been shown how High-level Grafcet can be used for structuring and scheduling algorithms [Wallén, 1995]. A tool for simple process identification from step response data has been developed using MATLAB [Wallén, 1999].

Milestones

Fall 1999 Finish thesis

External Contacts

Universities

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].

Industries

Of the informal contacts I have had with people from process industry, the one with Börje Eriksson from MoDo has been especially valuable for discussions as well as for obtaining industrial data and performing experiments.

Course Work

I have more than 80 credits and I do not intend to take any more courses.

Service to the Department

Teaching

I have been teaching assistant in the following courses:

Course	Last Taught
Computer Controlled Systems	Spring 1999
AK(FED)	Fall 1998
Real Time Systems	Fall 1996
AK(M)	Spring 1992

Initiatives

I have developed two laboratory experiments in CCS, one in Real-Time Systems, and (a modification of) one in Process Identification.

Administrative Duties

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.

Master Thesis Supervision

- Anders Karlsson, "Remote Control of a Mobile Robot Using Petri Nets"
- Mikael Danielsson, "Control of an Oscillatory Systems" (co-supervised with Karl Johan Åström)

Publications

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.

Nilsson, A., K.-E. Årzén, and T. F. Petti (1992): "Model-based diagnosis—State transition events and constraint equations." In *Preprints IFAC Symposium on AI in Real-Time Control.* Delft, The Netherlands.

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.

Wallén, A. (1999): "A tool for rapid system identification." In *Proceedings of the 1999 IEEE International Conference on Control Applications.*

Control of *E. coli* Cultivations

Mats Åkesson

Start of project	1994-09-01	**Plan**	PhD 1999
Supervisor	Per Hagander	**Course Credits**	75
Publications:	1 Lic. thesis, 2 journal articles, 8 conference articles.		

Research Problem and 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*. One of the difficulties encountered in *E. coli* cultivations is the formation of the metabolic by-product acetate in situations with excess glucose or under anaerobic conditions. This is a problem as accumulation of acetate tends to reduce cell growth and production of the desired protein.

The accumulation of acetate can be reduced by proper choices of strain, media, and cultivation conditions. In fed-batch cultures, where additional glucose is fed during the cultivation, the feed rate can be manipulated to restrict formation of acetate. A number of feeding strategies have been developed, however, the implementation is often complicated due to the lack of cheap and reliable on-line sensors. Furthermore, most strategies also require considerable process knowledge to work well. Typically a key process parameter, such as the critical growth rate above which acetate formation occurs, has to be known *a priori*. This is not always the case, especially not during expression of a recombinant protein when significant changes in the process behavior may occur.

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 require a minimum of process specific knowledge. Such a methodology will be a valuable tool for cutting the development time for new processes.

Research Approach

We consider substrate feeding in fed-batch cultures of *E. coli* in stirred bioreactors. The control algorithm is based on extremum control as well as gain scheduling and PID control. Analysis and design is based on simplified process models derived from mass balances and microbial physiology. Simulations are made using the MATLAB/Simulink environment, and experiments for evaluation and validation is performed together with academic and industrial partners.

Results

The problem of avoiding acetate accumulation is complicated due to the lack of cheap and reliable on-line sensors for the relevant quantities. An important step was therefore to develop a method for on-line detection of acetate formation, see [J-2]. 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.

The possibility to detect acetate formation on line was then used to develop a probing feeding strategy that avoids both acetate accumulation and glucose starvation [J-1]. Several simulations and experiments demonstrate the feasibility of the strategy and also show that process changes can be handled. A major advantage is that no *a priori* knowledge of strain- or construct-specific parameters are required.

The feeding strategy requires good control of the concentration of dissolved oxygen in the reactor. 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 has been investigated [C-1].

During the later stage of a cultivation one often reaches the maximum oxygen transfer capacity of the reactor. This imposes a new constraint on the feed rate, as anaerobic conditions also cause formation of acetate. The probing feeding strategy has therefore been extended to handle also the oxygen transfer constraint and several experiments have been performed with good results.

Milestones

Fall 1999 Complete PhD thesis

External Contacts

The research project is performed in collaboration with Pharmacia & Upjohn, Process R&D, Stockholm, Sweden, and the Department of Biotechnology, Lund University, Lund, Sweden. In November 1998 a new collaboration was initiated with Active Biotech, Lund Research Center AB.

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 June 1999 I have completed 75 credits out of 80 credits required for PhD degree.

Service to the Department

Teaching

I have been teaching assistant in the following courses

Course	Last Taught
Automatic Control, Basic Course	Fall 1997
Automatic Process Control	Spring 1999
Computer-controlled Systems	Spring 1998
Adaptive Control	Fall 1998

I have also given lectures in graduate courses at Linköping University, Linköping, Sweden and University Hospital MAS, Malmö, Sweden.

Initiatives

I have contributed to the development of course material in several courses, for example laboratory experiments in Automatic Process Control, Automatic Control (Basic Course), and Adaptive Control.

Administrative Duties

I was responsible for seminar documentation during 1995.

Master Thesis Supervision

I am currently involved in supervision of three MSc theses at the Department of Automatic Control and the Department of Biotechnology, Lund University. I also assisted in the supervision of the thesis by M. Templin (ISRN LUTFD2/TFRT–5550–SE).

Publications

Journal papers

[J-1] M. Åkesson, P. Hagander, and J. P. Axelsson. "A probing feeding strategy for *Escherichia coli* cultures." *Biotechnology Techniques*, 1999. (In press).

[J-2] M. Åkesson, E. Nordberg Karlsson, P. Hagander, J. P. Axelsson, and A. Tocaj. "On-line detection of acetate formation in *Escherichia coli* cultures using dissolved oxygen responses to feed transients." *Biotechnology and Bioengineering*, 1999. (In press).

Papers at International Conferences

[C-1] M. Åkesson and P. Hagander. "A gain-scheduling approach for control of dissolved oxygen in stirred bioreactors." Accepted to the 14th World Congress of International Federation of Automatic Control, July 5-9, 1999, Beijing, China.

[C-2] M. Åkesson, P. Hagander, and J. P. Axelsson. "Fermentation monitoring using feed rate transients." In Skjöldebrand and Trystram, Eds., *Proceedings of the 4th International Symposium on Automatic Control of Food and Biological Processes*, Gothenburg, Sweden, September 1998.

[C-3] 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." In Yoshida and Shioya, Eds., *Preprints of the 7th International Conference on Computer Applications in Biotechnology*, Osaka, Japan, June 1998.

[C-4] M. Åkesson, P. Hagander, and J. P. Axelsson. "A pulse technique for control of fed-batch fermentations." In *Proceedings of the 1997 IEEE Conference on Control Applications*, Hartford, Connecticut, USA, October 1997.

[C-5] M. Åkesson. "Integrated control and fault detection for a mechanical servo process." In *Proceedings of IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes*, Hull, UK, August 1997.

[C-6] 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.

[C-7] 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

[A-1] M. Åkesson, P. Hagander, and J. P. Axelsson. "A probing feeding strategy for recombinant *E. coli* cultivations." Invited lecture at the 9th European Congress on Biotechnology, July 11 – 15, 1999, Brussels, Belgium.

[A-2] M. Åkesson, P. Hagander, and J. P. Axelsson. "A probing feeding strategy for *E. coli* cultivations." In *Abstract book of 217th ACS National Meeting*, Anaheim, CA, USA, March 1999.

[A-3] M. Åkesson, P. Hagander, and J. P. Axelsson. "A probing approach for detection of acetate formation." In *Preprints of Reglermöte '98*, Lund, Sweden, June 1998.

[A-4] 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.

[A-5] 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.

Theses and Technical Reports

[T-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.

[T-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.

[T-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.

[T-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.