LINKÖPING UNIVERSITY
DIVISION OF AUTOMATIC CONTROL
ACTIVITY REPORT
2010

Contents

Chapter 1

Introduction

The Division of Automatic Control has produced annual reports of the current format since 1976. The first ones covered the fiscal and academic years from July to June, and since 1997 the reports have covered the fiscal years from January to December. The period June 1995 to December 1996 was covered in one report. The current annual report is conseqeuently number 34 in the series.

It is also the last one of the current format. In the future we will rely on the web for archival facts and issue regular overviews of our research that are less technical and of more general interest.

As highlights for 2010 the following events could be mentioned:

- Our sectretary since 1982, Ulla Salaneck retired on April 1, 2010. Lennart Ljung, who has been head of the control division since July 1, 1976, stepped down as head and was replaced by Svante Gunnarsson on July 1, 2010. Both these events were celebrated by a large garden party with most of the current and past co-workers of the division. See the pictures on the next page.

Figure 1.1: Photos from the celebration of Ulla and Lennart.

- Lennart Ljung received an honorary professorship of the Academy of Mathematics and Systems Science, the Chinese Academy of Sciences on July 28, 2010.

Figure 1.2: Professor Lei Guo hands over the diploma to Lennart Ljung.

- Henrik Ohlsson and Stig Moberg defended their doctoral theses.
- In addition, Rickard Falkeborn and Daniel Peterson completed their Techn. Lic. degrees.
- The SSF strategic research center MOVIII had final seminar with sophisticated visualizations in the Norrköping Visualization Dome on October 14, 2010.
- The new government national strategic research areas ELLIIT, and Security Link were launched under leadership from the group.

Research

Our research interests are focused on the following areas:

- *System Identification*: We are interested in a number of aspects ranging from industrial applications, to aspects of the fundamental theory and properties of algorithms.
- *Non-Linear and Hybrid Systems*: Here we are interested both in developing theory for nonlinear systems and to understand and utilize how modern computer algebraic tools can be used for practical analysis and design. Hybrid systems is an important and emerging field, covering problems of how to deal with systems with both discrete and continuous phenomena.
- *Sensor Fusion*: Techniques to merge information from several sensors are of increasing importance. We are involved in four different industrial applications of this kind, at the same time as we try to abstract the common underlying ideas. Particle filters play an important role in this context.
- *Robotics*: We have a close cooperation with ABB Robotics, and several projects concern modelling and control of industrial robots.
- *Optimisation for Control and Signal Processing*: Convex optimisation techniques are becoming more and more important for various control and signal processing applications. We study some such applications, in particular in connection with model predictive control.

Details of these research areas are given in the corresponding sections of this report.

Funding

We thank the Swedish Research Council (VR), the Swedish Agency for Innovation Systems (VINNOVA) and the Foundation for Strategic Research (SSF) for funding a major part of our research. The strategic research center MOVIII is funded by SSF. The Linnaeus center CADICS is funded by VR and the Industry Excellence Center LINK-SIC is funded by VINNOVA and industry.

Undergraduate Education

As can be seen in Appendix B, the Division of Automatic Control has extensive education activities with a large number of courses. The teaching staff of the division is also involved in education development and management of the engineering programs within Linköping University. Svante Gunnarson is resposible for the program area EF (Electronics, Physics and Mathematics). This includes the “Y-program” (Applied Physics and Electrical Engineering), which is an award-winning Linköping engineering education program. Inger Klein is the leader of the program area DM (Data and Media), which includes the “D-program” (Computer Science and Engineering).

Report Outline

In the following pages the main research results obtained during 2010 are summarised. More details about the results can be found in the list of articles and technical reports (See Appendices G and H. Numerals within brackets refer to the items of these appendices). These reports are available free of charge, most easily from our web-site. The next section describes how you can search for our publications in our database and download any technical report.

Network Services

Mail addresses

There are a number of ways you can access the work produced at this group. Most convenient is probably to email the person you wish to contact. The email addresses are listed in Appendix A together with a short personal presentation of each co-worker. Apart from these shorter but quite arbitrary email addresses you can always use the general form

Firstname.Lastname@isy.liu.se

e.g., Lennart.Ljung@isy.liu.se.

We also have the generic email address

Automatic.Control@isy.liu.se

or AC@isy.liu.se for short.

Finally, you can also retrieve reports and software electronically using our World Wide Web services. This is our preferred method of distributing reports.

World Wide Web

The most powerful way to get in touch with the group is probably by using our WWW service. The addresses to our main web page, as well as the web pages for the major centers are:

- `http://www.control.isy.liu.se`
- `http://www.moviii.liu.se`
- `http://www.cadics.isy.liu.se`
- `http://www.linksic.isy.liu.se`
- `http://www.liu.se/pic`
- `http://er-projects.gf.liu.se/~COFCLUO`

When you surf around in our WWW-environment you will find some general information over this group, the staff, seminars, information about undergraduate courses taught by the group and you have the opportunity to download technical reports produced at this group. This is the easiest way to access the group's work, just click and collect.

Our WWW service is always under development. We look forward to your feedback regarding this service. If you have any questions or comments, please send an email to our group of webmasters

rt_www@isy.liu.se

Publications Data Base

Selecting "Publications" in our web pages gives access to our publications data base. It allows you to search for publications by author, area, year, and/or publication type. You can also search for words in the title. The result of the search is given either as a clickable list of publications (choose HTML) or a list of BibTEX items (choose Bibtex). Clicking on the publication items brings you to the home page of the publication with further information. Department reports can always be downloaded from the home page, while articles and conference papers refer to a related department report that can be downloaded in .pdf format.

Chapter 2

Division of Automatic Control 1976–2010

During the period 1976 – 2010, 34 annual reports have been issued of the same format as the current one. Since future annual reports will have another format we will here summarize some aspects of the Division of Automatic Control over this period of 34 years, as it has been reflected in the annual reports.

2.1 Personnel

Over the years, the Division of Automatic Control has expanded from 7 to 55 employees. The development is illustrated in Figure 2.1. What has happened in recent years is primarily that the number of Post Docs and Assistant Professors (forskarassistenter) has increased significantly. The number of Ph. D. students has hovered around 20 to 30 for almost 20 years. This is in accordance with general trends in Swedish academia.

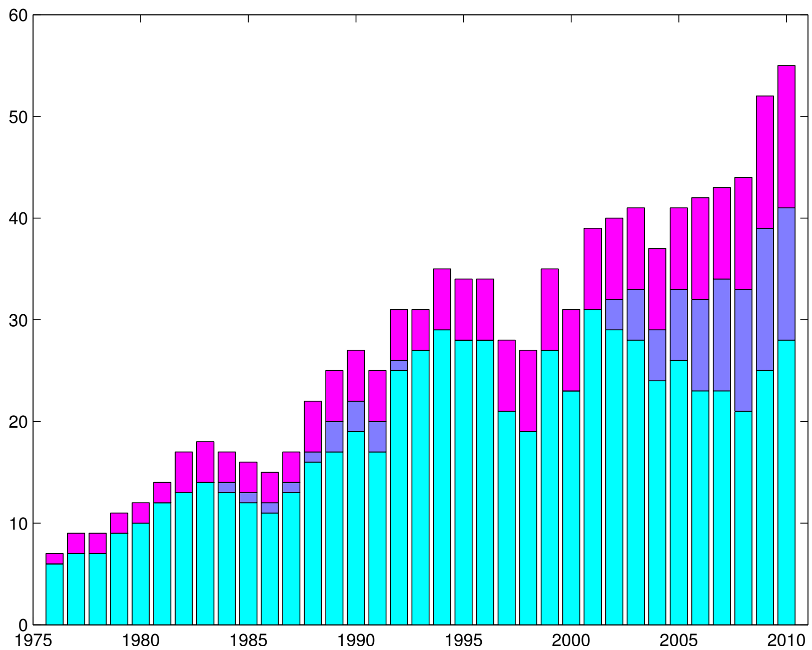


Figure 2.1: The number of employees over the years. The bars show, from above, (1) the number of professors/lecturers, (2) the number of Ph. D. with temporary positions and (3) the number of Ph. D. students and other personnel.

2.2 Scientific Production

The annual reports focus on the scientific results obtained during the years. How they are reported in books and other publications, and how they are received by fellow researchers is of course of major interest. These aspects are summarized in this section.

Each annual report lists published books, journal and conference papers, Ph. D., Techn. Lic. and M. Sc. theses. The accumulated figures are 21 books, 377 journal papers and 1067 conference publications, 64 Ph. D., 77 Techn. Lic. and 854 M. Sc. theses during the period 1976 – 2010.

2.2.1 Books

Twenty books (28 different editions) have been produced by the group during the period:

1. T. Glad and L. Ljung: *Reglerteknik — Grundläggande teori*, Studentlitteratur, Lund 1981, 200 pages, ISBN 91-44-17891-3. Second edition 1989, 250 pages, ISBN 91-44-17892-1. Third edition 2005. Fourth edition 2006, ISBN 978-91-44-02275-8.

2. L. Ljung: *Reglerteori — Moderna Analys- och Syntesmetoder*, Studentlitteratur, Lund 1981, 279 pages, ISBN 91-44-17901-4.

3. L. Ljung and T. Söderström: *Theory and Practice of Recursive Identification*, MIT Press, Cambridge, MA 1983, 529 pages. ISBN 0-262-12095-X.

4. L. Ljung: *System Identification — Theory for the User*, Prentice-Hall, Englewood Cliffs, NJ, 1987, 519 pages, ISBN 0-13-881640. Chinese translation: East China Normal University Press, Shanghai, 1990. Russian translation: Nauka, Moscow, 1991.

5. L. Ljung and T. Glad: *Modellbygge och Simulering*, Studentlitteratur, Lund 1991, 378 pages, ISBN 91-44-31871-5. Second edition 2004, 422 pages, ISBN 91-44-02443-6.

6. L. Ljung, G. Pflug and H. Walk: *Stochastic Approximation and Optimization of Random Systems*, Birkhäuser, Berlin, 1992, 113 pages, ISBN 3-7643-2733-2.

7. L. Ljung and T. Glad: *Modeling of Dynamic Systems*, Prentice Hall, Englewood Cliffs, NJ, 1994, 361 pages, ISBN 0-13-597097-0.

8. P. Lindskog, T. Glad and L. Ljung: *Modellbygge och simulering; Övningsbok*, Studentlitteratur, Lund, 1997, 233 pages, ISBN 91-44-00537-7.

9. T. Glad and L. Ljung: *Reglerteori. Flervariabla och olinjära metoder*, Studentlitteratur, Lund, 1997, 512 pages, ISBN 91-44-00472-9. Second edition 2003, 515 pages, ISBN 01-44-03003-7.

10. L. Ljung: *System Identification — Theory for the User*, Second edition, Prentice-Hall, Upper Saddle River, NJ, 1999, 607 pages, ISBN 0-13-656695-2. Chinese edition 2002.

11. F. Gustafson: *Adaptive Filtering and Change Detection*, Wiley, New York, 2000, 500 pages, ISBN 0-471-4987-6.

12. T. Glad and L. Ljung: *Control Theory: Multivariable and Nonlinear Methods*, Taylor & Francis, London, 2000, 467 pages, ISBN 0-7484-0878-9.

13. F. Gustafsson, L. Ljung and M. Millnert: *Signalbehandling*, Studentlitteratur, Lund, 2000, 455 pages, ISBN 91-44-01709-X.

14. F. Gunnarsson, F. Gustafsson and F. Tjärnström: *Signalbehandling, Övningsbok*, Studentlitteratur, Lund, 2000, 217 pages, ISBN 91-44-01501-1.

15. F. Gustafsson and N. Bergman: *Matlab for Engineers Explained*, Springer, London, 2003, 218 pages, ISBN 1-85233-697-8.

16. T. Glad and G. Hendeby (Eds): *Forever Ljung in System Identification*, Studentlitteratur, Lund, 2006, 282 pages, ISBN 91-44-02051-1.

17. P. Lindskog, T. Glad, L. Ljung and J. Roll: *Modellbygge och simulering övningsbok*, Second edition, Studentlitteratur, Lund, 2007, 294 pages, ISBN 1-44-05079-8.

18. F. Gustafsson, L. Ljung and M. Millnert: *Signal Processing*, Studentlitteratur, Lund, 2010, 397 pages, ISBN 1-44-05835-7.

19. F. Gunnarsson, F. Gustafsson and F. Tjärnström: *Signal Processing, Exercises*, Studentlitteratur, Lund, 2010, 229 pages, ISBN 9789144058368.

20. F. Gustafsson: *Statistical Sensor Fusion*, Studentlitteratur, Lund, 2010, 532 pages, ISBN 9789144054896.

2.2.2 Citations

Perhaps of more interest than the lists of publications themselves is to what extent they have influenced other researchers and engineers. The number of citations of the group's publications per year is shown in Figure 2.2. The accumulated number of citations is about 12 800.

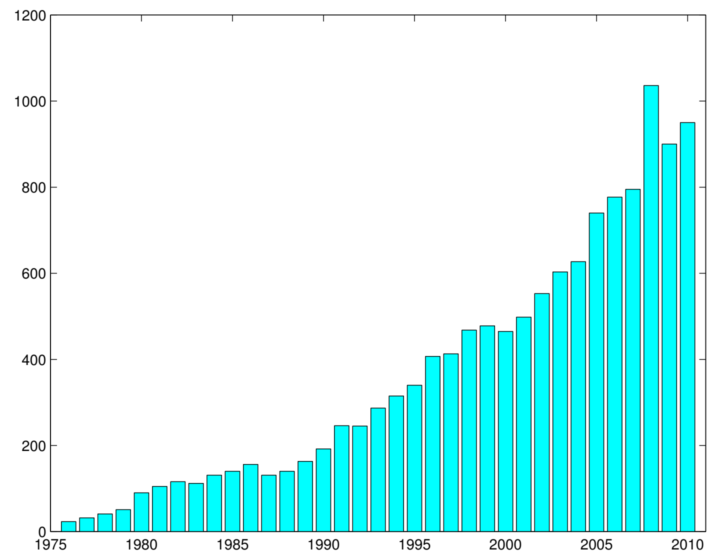


Figure 2.2: The number of yearly citations of the division's publications according to Science Citation Index (Web of Science).

Remark. The plot shows the number of citations according to the *Science Citation Index, Web of Science* to publications by the current supervisors in the control group, so that each paper is counted only once. In that way it does not cover publications by Ph. D. students and Assistant Professors, that are not co-authored by a (former) supervisor. Likewise, the Linköping production by prolific, former employees is not covered (like Bo Wahlberg, Björn Ottersten, Mats Viberg, Tomas McKelvey, Jonas Sjöberg and Håkan Hjalmarsson).

2.3 Graduate Exams

One of the most important aspects of research is its link to the graduate education. During 1976 – 2010, 64 graduates student have received their Ph. D. exam and 77 have received a Techn. Lic. exam. They will be listed here with currently known affiliations. The total number of graduate exams delivered in 1976 – 2010 is 141. The degrees have been awarded to a total of 89 different people.

2.3.1 Ph. D. Exams

For the Ph. D. exams we also include the name of the "Opponent". This is typically an international expert, who scrutinize the thesis during a public defense.

NAME	YEAR	OPPONENT	CURRENT AFFILIATION
Mille Millnert	1982	A. Willsky	Director General, Swedish Research Council (VR)
Ton van Overbeek	1982	K. Glover	European Space Agency, Holland
Bengt Bengtsson	1982	A. Segall	Sectra AB, Linköping (retired)
Stefan Ljung	1983	A. Benveniste	ABB, Ludvika
Henrik Jonson	1983	B. Qvarnström	SAAB Dynamics, Linköping
Eva Trulsson (Skarman)	1984	K.J. Åström	Melerit, Linköping
Kjell Nordström	1987	B. Egardt	Consultant, Norrköping
Bo Wahlberg	1987	M. Gevers	Professor, KTH, Stockholm
Svante Gunnarsson	1988	T. Söderström	Professor, LiTH
Alf Isaksson	1988	B. Friedlander	ABB, Västerås & Adjunct Professor, LiTH
Mats Viberg	1989	M. Kaveh	Professor, Chalmers
Krister Forsman	1991	M. Hazewinkel	Perstorp AB
Fredrik Gustafsson	1992	M. Basseville	Professor, LiTH
Peter Nagy	1992	H. Broman	FOI, Linköping
Tommy Svensson (Linderstam)	1992	D. Atherton	SAAB Dynamics, Linköping
Sören Andersson	1992	J. Böhme	Ericsson, Stockholm

PhD-exams, cont'd

NAME	YEAR	OPPONENT	CURRENT AFFILIATION
Håkan Hjalmarsson	1993	R. Kosut	Professor, KTH
Inger Klein	1993	P. Caines	Associate Professor, LiTH
Jan-Erik Strömberg	1994	H. Paynter	DST AB, Linköping
Ke Wang Chen (Helmersson)	1994	P. Mäkilä	Ericsson, Linköping
Thomas McKelvey	1995	J. Schoukens	Professor, Chalmers
Jonas Sjöberg	1995	G. Dreyfus	Professor, Chalmers
Roger Germundsson	1995	A. Benveniste	Wolfram Research, Champain, USA
Predrag Pucar	1995	B. Delyon	NIRA Dynamics
Håkan Fortell	1995	H. Sira Ramirez	ABB Robotics, Västerås
Anders Helmersson	1995	J. Maciejowski	Ruag Space, Linköping & Adjunct Professor, LiTH
Peter Lindskog	1996	H. Koivo	NIRA Dynamics, Linköping
Johan Gunnarsson	1997	R.S. Sreenivas	Sörman AB
Mats Jirstrand	1998	P.O. Gutman	Associate Professor, Frauenhofer, Chalmers
Urban Forssell	1999	B. Wahlberg	Öhlins Racing, Jönköping
Anders Stenman	1999	H. Hjalmarsson	NIRA Dynamics
Niclas Bergman	1999	V. Krishnamurthy	SAAB EDS
Krister Edström	1999	G. Dauphin-Tanguy	Ericsson SR, Lund
Magnus Larsson	1999	B. Neumann	ABB Robotics, Västerås
Fredrik Gunnarsson	2000	J. Zander	Ericsson, Linköping & Adjunct Professor, LiTH
Valur Einarsson	2000	S. Kowalewski	Einfalt ehf., Iceland
Mikael Norrlöf	2000	K. Moore	ABB Robotics, Västerås & Adjunct Professor, LiTH
Fredrik Tjärnström	2002	A. Vicino	Autoliv, Linköping
Johan Löfberg	2003	B. Foss	Assistant Professor, LiTH
Jacob Roll	2003	M. Morari	Autoliv, Linköping
Jonas Elbornsson	2003	A. Zoubir	Autoliv, Linköping
Ola Härkegård	2003	M. Bodson	SAAB AB, Linköping
Ragnar Wallin	2005	A. Garulli	Assistant Professor, LiTH

PhD-exams, cont'd

NAME	YEAR	OPPONENT	CURRENT AFFILIATION
David Lindgren	2005	B. DeMoor	FOI, Linköping
Rickard Karlsson	2005	N. Gordon	FOI, Linköping
Jonas Jansson	2005	H. Christensen	VTI, Linköping
Erik Geijer Lundin	2005	O. Salent	Scania AB
Martin Enqvist	2005	R. Pintelon	Associate Professor, LiTH
Thomas Schön	2006	S. Godsill	Associate Professor, LiTH
Ingela Lind	2006	T. Söderström	SAAB AB, Linköping
Jonas Gillberg	2006	P. van den Hof	Nynäs AB
Markus Gerdin	2006	M. Deistler	Imego AB, Göteborg
Christina Grönwall	2006	K. Åström	FOI, Linköping
Andreas Eidehall	2007	A. Polychronopoulos	Volvo AB, Göteborg
Frida Eng	2007	P. Ferreira	SP Devices, Linköping
Erik Wernholt	2007	J. Swevers	Autoliv, Linköping
Daniel Axehill	2008	M. Morari	Assistant Professor, LiTH
Gustaf Hendeby	2008	P.M. Djurić	DKFI, Kaiserslautern, Germany
Johan Sjöberg	2008	X. Hu	ABB CR, Västerås
David Törnqvist	2008	H. Durrand-Whyte	Assistant Professor, LiTH
Per-Johan Nordlund	2009	J. Lygeros	SAAB AB, Linköping
Henrik Tidefelt	2009	U. Jönsson	Wolfram Research
Henrik Ohlsson	2010	B. Wahlberg	Assistant Professor, LiTH
Stig Moberg	2010	B. Siciliano	ABB Robotics, Västerås

2.3.2 Techn. Lic. Exams

A "Techn. Lic." degree (teknologie licentiat) is a intermediate degree between Masters and Ph. D., around half-way to the Ph. D. This is the list of persons who received the Techn. Lic. degree from the Division of Automatic Control in 1976 – 2010, and are not part of the list in the previous section.

NAME	YEAR	CURRENT AFFILIATION
Peter Andersson	1983	
Gert Malmberg	1986	SAAB Dynamics
Karin Ståhl	1988	SAAB AB
Anders Skeppstedt	1988	SAAB Dynamics
Torbjörn Andersson (Crona)	1995	SAAB Dynamics
Jonas Plantin	1995	Ericsson
Anders Ericsson	1995	Ericsson SR
Jan Palmqvist	1997	SAAB AB
Magnus Andersson	1997	SAAB Dynamics
Jonas Blom	1998	Ericsson
Per Spångéus	1998	deceased
Anna Hagenblad	1999	deceased
Måns Östring	2002	Lecturer, LiTH, Norrköping
Claes Ohlsson	2002	
Niclas Persson (Sjöstrand)	2002	ABB Robotics
Svante Björklund	2003	FOI
Johanna Wallén	2008	LiTH (Ph. D. 2011)
Janne Harju Johansson	2008	ABB Ludvika
Jeroen Hol	2008	Xsens, Holland (Ph. D. 2011)
Daniel Ankelhed	2008	LiTH (Ph. D. 2011)
Per Skoglar	2008	LiTH (Ph. D. student)
Christian Lundqvist	2009	LiTH (Ph. D. student)
Christan Lyzell	2010	LiTH (Ph. D. student)
Richard Falkeborn	2010	Mathcore, Linköping
Daniel Petersson	2010	LiTH (Ph. D. student)

2.4 Undergraduate Teaching

2.4.1 Course Development

In the academic year 1976/77, the division offered two undergraduate courses with a total of 358 participants. These courses were:

1. Reglerteknik (Basic Control Course).

2. Reglerteori (Advanced Control Course).

Gradually, more and more undergraduate courses were introduced. In 2010 we had 1 278 participants in 18 different courses. Since the first courses in 1976/77, they have been developed to include the following categories:

3. The basic control course has been adapted and is given in six different formats for the various study programs, and degrees offered.

4. Digital Styrning (Digital Control), is incorporated from an earlier joint course in 1978. Remodeled, and renamed to Industriell Reglerteknik (Industrial Control Systems) in 2008.

5. Modellbygge och Simulering (Modeling and Simulation), introduced in 1980.

6. Digital Signalbehandling (Digital Signal Processing), introduced in 1986.

7. Reglerteknik M (Automatic Control, advanced course for Mechanical Engineering). Introduced in 1990.

8. Projektkurs (Project Oriented Course), introduced in 1990. Remodeled to adjust to CDIO norms in 2000.

9. Optimal Styrning (Optimal Control), introduced in 2009.

10. Sensorfusion (Sensor Fusion), introduced in 2009.

See Section B.1 for the number of participants and undergraduate course material available during the year 2010.

2.4.2 Master's Theses

Since 1976, 854 Master's theses have been produced. In many cases a thesis is written by two students, so the number of Master's thesis students examined is about 1200.

2.4.3 Quality Measures

- The students give the courses high rating in the course evaluations. As a result of that the teaching staff has received approximately 40 letters of recognition from the Dean of LiTH, distributed over thirteen staff members. Such a letter is given to a course that gets rating 4.2 or more on a 1 to 5 scale for course quality. (Approximately 10 % of the courses given within the engineering programs every year receive such a letter.) This is since 2002, when the Dean started this practice.

- Members of the teaching staff have been nominated to the award Gyllene Moroten ("Teacher of the Year") nine times by the student union within LiTH. In 2009, Thomas Schön won the award.

- Members of the teaching staff have eight times received the award Iplom for high course ratings from the student within the program Industrial Engineering and Management.

- In 2007, the study area *Control Systems* in Linköping (which consists of the Automatic Control group and the Vehicular Systems group) received the award for "Excellent Education Environment" (Utmärkelsen "Framstående Utbildningsmiljö") from the Swedish National Agency for Higher Education (Högskoleverket). The award was given to five such environments across all areas at all Swedish universities.

2.5 Major Grants and Research Centra

The need and expectations to bring in external research funds has increased dramatically over the period. The first external grant was given by STU (Styrelsen för Teknisk Utveckling) in 1979 and concerned fast solution of integral equations. Since then there has been many grants from STU, STUFF, NUTEK, TFR, VR, NFFP, VINNOVA, SSF and other funding agencies. Among major grants supporting broad centra (with the Division of Automatic Control as organizer and "Principal Investigator") we may mention:

- ISIS (Integrated Systems for Control and Supervision). A NUTEK/VINNOVA Competence center, 1995 – 2005.

- VISIMOD (Visualization, Simulation and Modeling). A Research program funded by SSF, 2002 – 2007.

- MOVIII (Modeling, Visualization and Information Integration). A Strategic Research Center, funded by SSF, 2006 – 2010.

- CADICS (Control, Autonomy and Decision Support in Complex Systems). A Linnaeus Research Center, funded by VR (the Swedish Research Council), 2008 – 2018.

- LINK-SIC (Linköping Excellence Center for Sensor Informatics and Control). An Industrial Excellence Center, funded by VINNOVA and industry, horizon 2007 – 2017.

- COFCLUO (Clearance of Flight Control Laws Using Optimization), An EC project under the 6th Framework Programme, 2007 – 2010.

- PIC-LI (Process Industry Center - Linköping) A research and competence center funded by SSF, 2008 – 2013.

- ELLIIT (Excellence Center at Linköping-Lund in Information Technology). One of the Strategic Research Areas (SFO) that the government initiated 2010. It is focused on Information Technology and mobile communication. Horizon 2010 and onward.

- SECURITY LINK. Another of the SFOs focused on security issues in a broad sense. Horizon 2010 and onward.

Chapter 3

System Identification

The system identification research within the group concerns both theoretical aspects and applications in a number of areas, e.g., aircraft, industrial robots, medical imaging, and navigation sensors. During 2010, two Ph. D. theses about system identification were defended. Henrik Ohlsson's thesis *Regularization for Sparseness and Smoothness* [2] is described in this chapter, while Stig Moberg's thesis *Modeling and Control of Flexible Manipulators* [1] is described in Chapter 6.

During the year, also the perspective paper [26] was published. It is based on the 2008 plenary lecture at the IFAC World Congress in Seoul.

3.1 Regularization for Sparseness and Smoothness

Regularization shows up in a variety of different situations and is a well-known technique to handle ill-posed problems and to control for overfit. In statistics and machine learning, regularization has gained popularity due to modeling methods such as *Support Vector Machines* (SVM), *ridge regression* and *lasso*. But also when using a *Bayesian* approach to modeling, regularization often implicitly shows up and can be associated with the prior knowledge. Regularization has also had a great impact on many applications, and very much so in clinical imaging. In e.g., breast cancer imaging, the number of sensors is physically restricted, which leads to long scan times. Regularization and sparsity can be used to reduce that. In *Magnetic Resonance Imaging* (MRI), the number of scans is physically limited and to obtain high resolution images, regularization plays an important role.

Henrik Ohlsson's thesis [2] focuses on the use of regularization to obtain sparseness and smoothness and discusses novel developments relevant to system identification and signal processing. In regularization for sparsity a quantity is forced to contain elements equal to zero, or to be sparse. The quantity could e.g., be the regression parameter vector of a linear regression model and regularization would then result in a tool for variable selection. Sparsity has had a huge impact on neighboring disciplines, such as machine learning and signal processing, but rather limited effect on system identification. One of the major contributions of Henrik's thesis is therefore the new developments in system identification using sparsity. In particular, a novel method for the estimation of segmented ARX models using regularization for sparsity is presented [30]. A technique for piecewise-affine system identification is also elaborated on, as well as several novel applications in control [62] and signal processing [61]. Another property that regularization can be used to impose is smoothness. To require the relation between regressors and predictions to be a smooth function is a way to control for overfit. Henrik has been particularly interested in regression problems with regressors constrained to limited regions in the regressor-space, e.g., a manifold. For this type of systems a new regression technique, *Weight Determination by Manifold Regularization* (WDMR, see e.g., Ohlsson and Ljung [29], Bauwens et al. [8]) was developed. WDMR is inspired by applications in biology and developments in manifold learning and uses regularization for smoothness to obtain smooth estimates. The use of regularization for smoothness in linear system identification is also discussed.

Henrik's thesis also presents a real-time *functional Magnetic Resonance Imaging* (fMRI) bio-feedback setup. The setup has served as proof of concept and been the foundation for several real-time fMRI studies, e.g., Nguyen et al. [59], Eklund et al. [42, 41].

3.2 Nonlinear Systems

Identification of nonlinear systems is a vast subject, with many suggested model structures and algorithms. The area has sometime been called "non-elephant" zoology, to pinpoint how difficult it is to characterise and classify it. An attempt to provide some kind of structure into the field is given in [55].

3.2.1 State-space Descriptions

During the last decade or so, nonlinear system identification techniques based on sequential Monte Carlo (SMC) methods, such as particle filters, have appeared at an increasing rate and with increasingly better performance. In the papers [60, 53] we have continued this line of work. More specifically, we employ the standard Maximum Likelihood (ML) framework and derive an Expectation Maximization (EM) type algorithm. This involves the solution of a nonlinear smoothing problem for the state variables.

In the work [60] we provide a novel approach to the estimation of a general class of dynamic nonlinear system models. The main contribution is the use of a tool from mathematical statistics, known as Fishers' identity, to establish how an EM type quantity can be used to compute gradients of maximum-likelihood and associated prediction error cost criteria.

Furthermore, in [53] we developed an identification method capable of identifying parameters in so called mixed linear/nonlinear state-space models, containing conditionally linear Gaussian substructures. For this cause, we develop a so called Rao-Blackwellized particle smoother (RBPS), designed to exploit the structure present in a mixed linear/nonlinear state-space model. By doing so, we can obtain better estimates than what is provided by a standard particle smoother, using the same number of particles.

The EM algorithm has proven to be effective for a range of identification problems. Unfortunately, the way in which the EM algorithm has previously been applied has proven unsuitable for the commonly employed innovations form model structure. In the work [74] we address this problem, and present a previously unexamined method of EM algorithm employment. The results are profiled, which indicate that a hybrid EM/gradient-search technique may in some cases outperform either a pure EM or a pure gradient-based search approach

3.2.2 Block-oriented Systems

A block-oriented system consists of a combination of linear dynamic subsystems and static nonlinearities, connected either in series or in parallel. This system class contains well-known and well-studied sub-classes, such as Wiener, Hammerstein and Wiener-Hammerstein systems. Many of the existing methods for these types of systems are based on, or benefit from, a theoretical result known as the invariance property. For example, Bussgang's classic theorem shows that this property holds for a static nonlinearity with a Gaussian input signal. The book chapter [13] contains an introduction to the invariance property and explains why it is so useful for identification of block-oriented systems.

The special problem of a *Wiener model* concerns the case of a linear dynamic system followed by a static nonlinearity. In [32] it is shown how to formulate the ML criterion for this structure, also in the case additive *colored* noise enters into or after the linear system. Handling this criterion numerically is non-trivial, but in the paper it is pointed out how to deal with the problem using particle filtering. As an extra benefit, also follows a method to deal with *blind Wiener* models, that is systems without measurable inputs, which obey the structure: white noise entering an unknown linear dynamic system, followed by a nonlinear static block.

3.3 Continuous-time Models

3.3.1 Sampling Continuous-time Models with Stochastic Disturbances

The basic continuous-time (CT) model

$$\begin{aligned}\dot{x} &= Ax + Bu + w\\ y &= Cx + e\end{aligned}$$

is an idealisation that contains mathematically sophisticated objects like CT *white noises* w and e. Sampling such models to describe real world discrete time signals must involve some kind of low-pass filtering of y. In connection with system identification of CT models from sampled data, this process is often approximated (or "mishandled") to some extent. In [27] it is discussed how a proper method should work and to what extent the usual methods capture or not the essential features.

3.3.2 Estimation of Continuous-time Models using Frequency Domain Techniques

The two companion papers [14] and [15] concern the problem of estimating a CT model

$$y(t) = \frac{B(p)}{F(p)} u(t) \tag{3.1}$$

where p is the differentiation operator, from sampled data sequences $y(t_k)$, $u(t_k)$, $k = 1, \ldots, N$.

The basic approach is to form the discrete Fourier transforms (DFT) of the input output data, and see how they can be used to obtain good estimates of the true (continuous-time) Fourier transforms. Then frequency domain criteria can be used to estimate (3.1). Part I of the two papers [14, 15] concerns the case of uniformly sampled data ($t_k = kT$), while part II deals with the general, non-uniformly sampled case.

3.4 Applications

The paper [23] is concerned with the problem of estimating the relative translation and orientation of an inertial measurement unit and a camera, which are rigidly connected. The key is to realize that this problem is in fact a gray-box system identification problem, the paper is also discussed in Chapter 5 on sensor fusion. Another system identification type problem appears in [51], where we provide a novel method for calibrating an Ultra-Wideband (UWB) indoor positioning system. This is again further explained in the chapter on sensor fusion, since it also involves interesting sensor fusion aspects.

Gray-box identification of industrial robots is described in [31] and in Stig Moberg's Ph. D. thesis [1]. More information about this application is available in Chapter 6.

An application of identification to systems biology is described in [9]. The model describes insulin signaling in human cells and the problem is to reject certain choices of structure. More details are given in Chapter 4 on nonlinear and DAE models.

Chapter 4

Nonlinear and DAE Models

4.1 Structure of DAE Models

An important structural property of a differential algebraic equation (DAE),

$$F(\dot{x}, x, t) = 0$$

is the number of hidden implicit differentiations. This is closely related to the practical difficulty of rewriting the DAE as an explicit ordinary differential equation (ODE). A widely used measure of this difficulty is the Kunkel-Mehrmann strangeness index. A relaxation of the strangeness index that has a very simple characterization was presented in the previous annual report for 2009. In [118] the properties of this simplified index were developed further.

4.2 Rejection of Models based on Qualitative Properties

Consider a fairly general model of a physical system

$$\dot{x} = f(x, \theta), \quad y = h(x, \theta)$$

where y is the measured output, x is the state vector and θ is a vector of constant parameters. Often the modeling problem has the two phases of first choosing the function f, which relates to the structure of the system, and then finding suitable values for θ. Sometimes it is useful to reject a model structure, i.e., to show that, for a given f, there is no physically reasonable choice of θ that is compatible with the measured values of y.

One application where this problem comes up is systems biology. A typical model can be described by a diagram like the one shown in Figure 4.1, that describes how the concentrations of four different proteins affect each other.

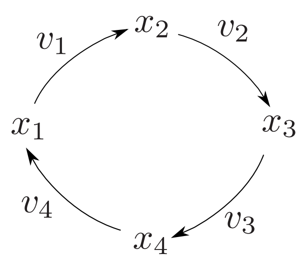


Figure 4.1: Chemical reactions that transform proteins.

Mathematically the model is

$$
\begin{aligned}
\dot{x}_1 &= -v_1(x_1) + v_4(x_4) \\
\dot{x}_2 &= -v_2(x_2) + v_1(x_1) \\
\dot{x}_3 &= -v_3(x_3) + v_2(x_2) \\
\dot{x}_4 &= -v_4(x_4) + v_3(x_3)
\end{aligned}
$$

where the state variables are the protein concentrations and the functions v_i are the reaction velocities. Models of this type can be used to describe insulin signaling in cells, as shown in [9]. In the simplest models the velocities are modeled as being linear, but more realistic models include saturation effects. In experiments x_1 is intialized with a certain concentration and one of the other concentrations is measured. The response then shows a pronounced overshoot. The question is then: when can a model of this form have an overshoot? In the linear case this question is closely related to the plcement of poles and zeros. For instance one can show that when v_3 is much smaller than the other velocities there can be no overshoot in a measurement of x_4, but there will be a large overshoot in x_2, associated with a zero close to the imaginary axis. See the illustration given in Figure 4.2.

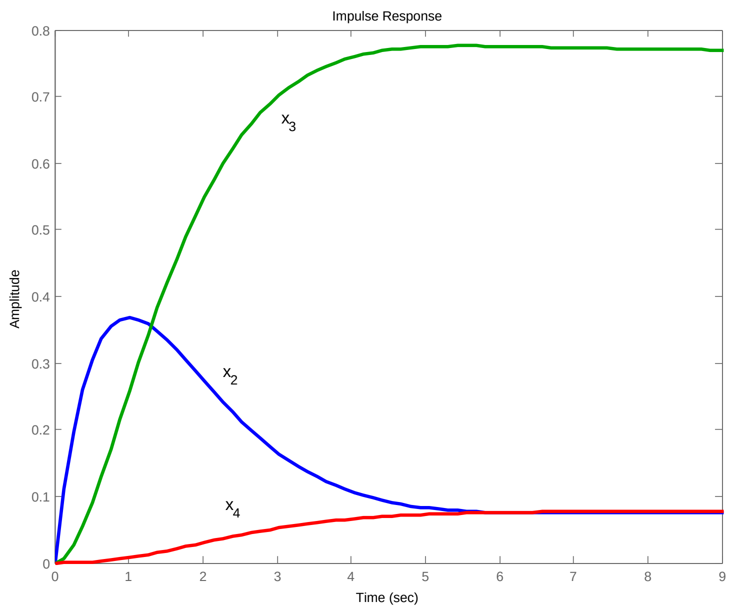


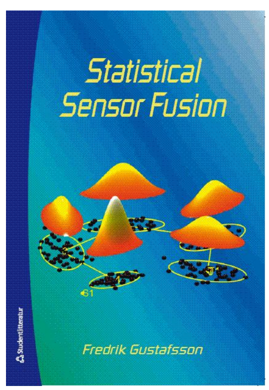
Figure 4.2: Responses of a biochemical reaction when v_3 is small.

Chapter 5

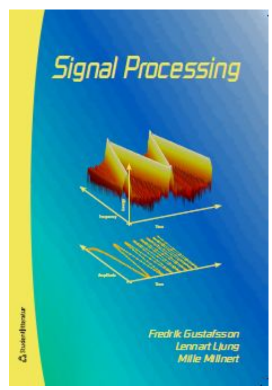
Sensor Fusion

Highlights of the year are:

- The books on sensor fusion [5] and signal processing [6].



(a) Sensor Fusion [5]



(b) Signal Processing [6]

- The magazine article [17], which summarizes 20 years experience in using wheel speed sensors for application with high demand on accuracy. It describes pre-processing to compensate for sensor imperfections, interpolation from event domain to time domain, synchronous sampling, and various automotive applications.

- The magazine article [16], which contains a tutorial on the particle filter aimed for practitioners with a background in Kalman filter applications. It overviews the connection to the point mass filter, the basic theory, practical implementation aspects such as numerical issues, Matlab code and marginalization, and summarizes a fair amount of applications from the group.

- The scientific publications, including the journal papers [11, 23, 21, 22, 28, 10, 17, 16, 24] and the conference papers [63, 48, 67, 57, 54, 56, 47, 68, 45, 51, 50, 72, 36, 69, 53, 38, 65, 64, 35, 60, 46, 71, 39].

5.1 Book Overviews

Statistical Sensor Fusion

Sensor fusion deals with merging information from two or more sensors, where the area of statistical signal processing provides a powerful toolbox to attack both theoretical and practical problems.

The objective of this book is to explain state of the art theory and algorithms in statistical sensor fusion, covering estimation, detection and nonlinear filtering theory with applications to localization, navigation and tracking problems. The book starts with a review of the theory on linear and nonlinear estimation, with a focus on sensor network applications. Then, general nonlinear filter theory is surveyed, with a particular attention to different variants of the Kalman filter and the particle filter. Complexity and implementation issues are discussed in detail. Simultaneous localization and mapping (SLAM) is used as a challenging application area of high-dimensional nonlinear filtering problems.

The book spans the whole range from mathematical foundations provided in extensive appendices, to real-world problems covered in a part surveying standard sensors, motion models and applications in this field. All models and algorithms are available as object-oriented Matlab code with an extensive data file library, and the examples, which are richly used to illustrate the theory, are supplemented by fully reproducible Matlab code.

Signal Processing

This edition has evolved over the past twenty years, the first ten years as a compendium and then as a textbook in Swedish. It has been used in a course in Signal Processing at Linköping University by around 1500 undergraduate students from all engineering programs. Already from the start, it distinguished itself from the large amount of textbooks on signal processing by shifting the focus from transform theory to a comprehensive treatment of classical (transform based) as well as modern (model based) signal processing aimed at applications on real data and problems. The selection of topics is guided by the topics of more than 200 external M. Sc. theses in signal processing as well as the needs from our many industrial research partners. With this first international edition, we have further increased the connection to Matlab. The general idea is that each topic should lead to an algorithm with a compact Matlab function. These Matlab functions gradually adds functionality to the reader's versatile signal processing toolbox, where only standard Matlab is needed. However, each chapter summary also points out which functions are already available in the signal processing, control and system identification toolboxes. The presented functions are a part of Signal and Systems Lab, a toolbox taylored to the theory of this book. The lab contains a database of real signals the reader can play around with, many of these are used in the examples. All non-trivial examples of the book includes reproducible code, and all functions and examples in the book are included in the installation. There is also an accompanying book with exercises, also with a practical focus with a mix of problem solving by hand and Matlab programming. See also the publisher's homepage.

5.2 Project Overview

Our research in sensor fusion covers the whole chain of problems, from sensors to applications, as illustrated in Figure 5.1:

- *Sensor and dynamic motion models*
  - *Sensor modeling* is focused on inertial measurement units (IMU) and using cameras as sensors. The problems involve sensor error modeling, outlier detection and measurement uncertainty assessment.
  - *Sensor-near signal processing* problems needed between the sensors and the sensor fusion block are also essential.
  - *Modeling for state estimation*, including kinematic and dynamic models for the applications below. The field tests we are working on involve power measurements from received radio, acoustic, seismic and magnetic waves.

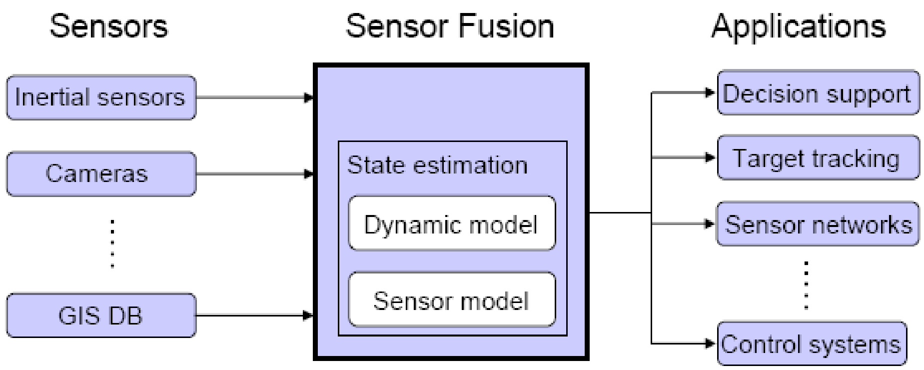


Figure 5.1: Structure of a sensor fusion system and this chapter.

- *State estimation*
  - *Particle filtering.* The theoretical research focuses on obtaining scalable and real-time algorithms for sensor fusion applications, where marginalization is the key tool.
  - Detection, localization and tracking in *sensor networks*.
  - *Target tracking* problems.

- *Sensor fusion applications*
  - *Localization and tracking.* The vision and mission are to position everything that moves. We have applications to aircraft, rockets, cars, surface ships, underwater vessels, film cameras, cellular phones and industrial robots. One leading theme is to consider cameras and Geographical Information Systems (GIS) as standard sensors in sensor fusion. A technical driver is to backup, support or replace GPS in critical integrated navigation systems. In some cases, the (extended) Kalman filter is used in our application, but in particular when GIS are used, the particle filter and marginalized particle filter mentioned above are applied.
  - *Simultaneous localization and mapping (SLAM).* Our goal is to develop full 3D SLAM running on UAVs (SAAB, FOI).
  - *Situation awareness* and detection algorithms. In particular, collision mitigation and avoidance systems for cars (Volvo) and aircrafts (SAAB).

The current funding comes from Swedish Research Council (VR), MOVIII (SSF excellence center), NFFP decisions based on uncertain data, NRFP fusion of IMU and GPS in rockets, ARCUS (TAIS) path planning of UAVs, and FOCUS (VINNOVA institute excellence center) on sensor networks.

5.3 Localization, Navigation and Mapping

5.3.1 Silent Localization of Underwater Sensors

The publication [11] is about sensor localization, which is a central problem for sensor networks. If the sensor positions are uncertain, the target tracking ability of the sensor network is reduced. Sensor localization in underwater environments is traditionally addressed using acoustic range measurements involving known anchor or surface nodes. We explore the usage of triaxial magnetometers and a friendly vessel with known magnetic dipole to silently localize the sensors. The ferromagnetic field created by the dipole is measured by the magnetometers and is used to localize the sensors. The trajectory of the vessel and the sensor positions are estimated simultaneously using an extended Kalman filter. Simulations show that the sensors can be accurately positioned using magnetometers.

5.3.2 Joint Ego-Motion and Road Geometry Estimation

In the article [28] we provide a sensor fusion framework for solving the problem of joint ego-motion and road geometry estimation. More specifically we employ a sensor fusion framework to make systematic use of the measurements from a forward looking radar and camera, steering wheel angle sensor, wheel speed sensors and inertial sensors to compute good estimates of the road geometry and the motion of the ego vehicle on this road. In order to solve this problem we derive dynamic models for the ego vehicle, the road and the leading vehicles. The main difference to existing approaches is that we make use of a new dynamic model for the road. An extended Kalman filter is used to fuse data and to filter measurements from the camera in order to improve the road geometry estimate. The proposed solution has been tested and compared to existing algorithms for this problem, using measurements from authentic traffic environments on public roads in Sweden. The results clearly indicate that the proposed method provides better estimates.

5.3.3 Random Set Based Road Mapping

The work [56] is concerned with the problem of multi-sensor multi-target tracking of stationary road side objects, i.e., guard rails and parked vehicles, in the context of automotive active safety systems. Advanced active safety applications, such as collision avoidance by steering, rely on obtaining a detailed map of the surrounding infrastructure to accurately assess the situation. Here, this map consists of the position of objects, represented by a random finite set (RFS) of multi-target states and we propose to describe the map as the spatial stationary object intensity. This intensity is the first order moment of a multi-target RFS representing the position of stationary objects and it is calculated using a Gaussian mixture probability hypothesis density (GM-PHD) filter.

5.3.4 Estimating Polynomial Structures from Radar Data

Situation awareness for vehicular safety and autonomy functions includes knowledge of the drivable area. This area is normally constrained between stationary road-side objects as guard-rails, curbs, ditches and vegetation. In [57] we consider these as extended objects modeled by polynomials along the road, and propose an algorithm to track each polynomial based on noisy range and bearing detections, typically from a radar. A straightforward Kalman filter formulation of the problem suffers from the errors-in-variables (EIV) problem in that the noise enters the system model. We propose an EIV modification of the Kalman filter and demonstrates its usefulness using radar data from public roads.

5.3.5 Fingerprinting Localization in Wireless Networks Based on RSS Measurements

Localization in wireless networks based on received-signal-strength (RSS) observations is a challenging problem. This is mainly due to the noisy characteristics of the RSS measurements which are influenced a lot by non-line-if-sight and multi-path effects. Modeling such phenomena is very difficult using mathematical models if not impossible. Hence, maps of different RSS measurements called *fingerprints* collected from different points in the area of surveillance are experimentally obtained and used later for localization. Our work [10] shows how such maps can be utilized in particle filters as a form of a measurement model. The results of the proposed approaches are illustrated and compared with an example whose data were collected from a WiMAX network in a challenging urban area in Brussels, Belgium.

5.3.6 Modeling and Calibration of Inertial and Vision Sensors

The paper [51] is concerned with the problem of estimating the relative translation and orientation of an inertial measurement unit and a camera, which are rigidly connected. The key is to realize that this problem is in fact an instance of a standard problem within the area of system identification, referred to as a gray-box problem. We propose a new algorithm for estimating the relative translation and orientation, which does not require any additional hardware, except a piece of paper with a checkerboard pattern on it. The method is based on a physical model which can also be used in solving, for example, sensor fusion problems. The experimental results show that the method works well in practice, both for perspective and spherical cameras.

5.3.7 Geo-referencing for UAV Navigation using Environmental Classification

The paper [54] considers the problem of UAV navigation. In particular, we seek a GPS free navigation system that does not suffer from long term drift. A UAV navigation system relying on GPS is vulnerable to signal failure, making a drift free backup system necessary. Here, we introduce a vision based geo-referencing system that uses preexisting maps to reduce the long term drift. The system classifies an image according to its environmental content and thereafter matches it to an environmentally classified map over the operational area. This map matching provides a measurement of the absolute location of the UAV that can easily be incorporated into a sensor fusion framework. Figure 5.2 shows experimental results using data collected during a test-flight in southern Sweden. The experiments show that the geo-

Figure 5.2: True trajectory illustrated with circles and the estimated trajectories with (solid line) and without (dashed line) geo-referencing. By comparing the images from an on-board camera with an existing map of the operational environment, the long term drift in the position estimate can be reduced.

referencing system reduces the long term drift in UAV navigation, enhancing the ability of the UAV to navigate accurately over large areas without the use of GPS, see Figure 5.2.

5.3.8 Learning to Close the Loop from 3D Point Clouds

For mobile robots and autonomous vehicles, the ability to recognize previously visited places is important, especially in the Simultaneous Localisation and Mapping (SLAM) problem. Place recognition, also known as loop closure detection, has been addressed for robots equipped to acquire three dimensional laser range data, called point clouds [47]. The point clouds are given a mathematical description using more than 40 features that describe the geometric and statistical properties of the data. The features are rotation invariant, enabling loop closure detection from arbitrary direction.

Features from two point clouds are compared using an AdaBoost learned classifer. AdaBoost is an iterative machine learning algorithm which builds classifiers by concatenating simple, so called “weak”, classifiers. With the learned classifier, 63% and 53% detection rates are achieved at 0% false alarm, for outdoor and indoor data, respectively. Experiments where the classifier is learned using outdoor data and tested using indoor data from a different sensor setup show the classifiers strong generalisation capabilities. Figure 5.3 shows a two dimensional projection of the resulting SLAM map from one of the experiments.

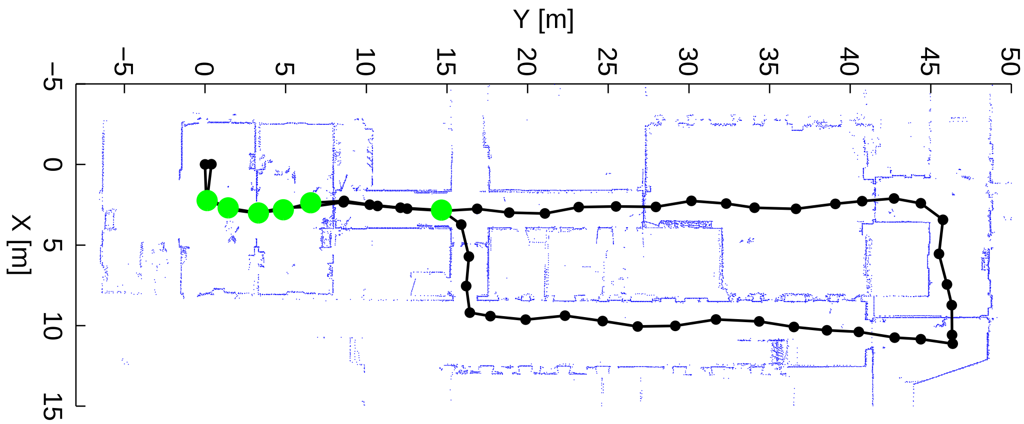


Figure 5.3: 2D projection of 3D SLAM map. The laser points are shown in blue, the robot trajectory is shown with black circles. The detected loops are marked with large green circles.

5.3.9 Ultra-Wideband Calibration for Indoor Positioning

The main contribution of this work is a novel calibration method to determine the clock parameters of the UWB receivers as well as their 3D positions. It exclusively uses time-of-arrival measurements, thereby removing the need for the typically labor-intensive and time-consuming process of surveying the receiver positions. Experiments show that the method is capable of accurately calibrating a UWB setup within minutes.

5.3.10 Probabilistic Stand Still Detection using Foot Mounted IMU

The paper [36] is about stand still detection for indoor localization based on observations from a foot-mounted inertial measurement unit (IMU). The main contribution is a statistical framework for stand-still detection, which is a fundamental step in zero velocity update (ZUPT) to reduce the drift from cubic to linear in time. First, the observations are transformed to a test statistic having non-central χ^2 distribution during zero velocity. Second, a hidden Markov model is used to describe the mode switching between stand still and moving. The resulting algorithm computes the probability of being in each mode, and it is easily extendable to a dynamic navigation framework where map information can be included. Results of mode probability estimation are provided.

5.3.11 Simultaneous Navigation and SAR Autofocusing

In the work [69] we present a method of using Synthetic Aperture Radar (SAR) images and focus information in these together with the navigation system. This information is combined together in a sensor fusion framework and improvement to both navigation state estimate and image focus is obtained. The method is evaluated on a representative simulated test images and the results are promising.

5.3.12 Window Based GPS Integrity Test using Tight GPS/IMU Integration

This work [71] presents integrity monitoring and integration methods for an Inertial Measurement Unit (IMU) and a GPS receiver. The methods are applied to data from a Maxus sounding rocket used for microgravity research. It is crucial to determine the rocket position during launch to ensure a safe landing location. Today, the navigation relies on IMU integration only. Involving a GPS receiver enhances the position accuracy but there is a need for protection against faulty satellite range measurements. Monitoring over a sequence of the measurements gives higher confidence to the tests.

5.4 Particle Filtering

5.4.1 Particle Filtering — The Need for Speed

The particle filter (PF) is sometimes believed to be trivially parallelized on multi-core processors, since each core can be responsible for the operations associated with one or more particles. This is true for the most characteristic steps in the PF algorithm applied to each particle, but not for the interaction steps. Further, as is perhaps less well known, the bottleneck computation even on CPU's is often not the particle operations but the re-sampling, and this is not obvious to parallelize.

The main steps in the PF and their complexity as a function of N number of particles are discussed in [21], and are summarized in words below:

- Initialization: each particle is sampled from a given initial distribution and the weights are initialized to a constant. Parallelizable and thus $\mathcal{O}(1)$.
- Measurement update: The likelihood of the observation is computed conditional on the particle. Parallelizable and thus $\mathcal{O}(1)$.
- Weight normalization: The sum of the weight is needed for normalization. A hierarchical evaluation of the sum is possible, which leads to complexity $\mathcal{O}(\log(N))$.
- Estimation: The weighted mean is computed. This requires interaction. Again, a hierarchical sum evaluation leads to complexity $\mathcal{O}(\log(N))$.
- Re-sampling: This step first requires the weights to be sorted. Sorting is an $\mathcal{O}(\log(N))$ operation, and it is not obvious how to parallelize it. There are other similar interaction steps.
- Prediction: Each particle is propagated through a common proposal density. Parallelizable and thus $\mathcal{O}(1)$.
- Optional steps of Rao-Blackwellization: If the model has a linear Gaussian substructure, a part of the state vector can be updated with the Kalman filter. This is done locally for each particle, and thus $\mathcal{O}(1)$.
- Optional step of computing marginal distribution of the state (the filter solution) rather than the state trajectory distribution. This is $\mathcal{O}(N^2)$ on a single core processor, but parallelizable to $\mathcal{O}(N)$. It also requires massive communication between the particles.

This suggests the following basic functions of complexity:

$$\begin{aligned} \text{Single-core:} \quad & f_1(N) = c_1 + c_2 N \\ \text{Multi-core:} \quad & f_M(N) = \frac{N}{M}\Big(c_3 + c_4 \log(N)\Big) \end{aligned}$$

In the future, we might be able to use $N = M$ above. Eventually, the multi-core implementation will always be more efficient as $N \to \infty$. However, for the value of N that the application requires, the best solution depends on the constants. One can here define a break-even number

$$N_{\text{breakeven}} = \text{sol}_N c_1 + c_2 N = \frac{N}{M}\Big(c_2 + c_3 \log(N)\Big)$$

This number depends on the relative processing speed of the single and multi-core processors, but also on how efficient the implementation is.

It is the purpose of this contribution to discuss these important issues in more detail, with a focus on general purpose graphical processing units (GPGPU). We also provide one of the first complete GPGPU implementations of the PF, and use this example as a ground for a discussion of $N_{\text{breakeven}}$.

5.4.2 The Rao-Blackwellized Particle Filter — A Filter Bank Implementation

In our earlier publications, we have derived the marginalized particle filter (MPF) , Rao-Blackwellized particle filter, in terms of a structured model of the form

$$\begin{aligned}
x^n_{k+1} &= f^n_k(x^n_k) + F^n_k(x^n_k)x^l_k + G^n_k(x^n_k)v^n_k \\
x^l_{k+1} &= f^l_k(x^n_k) + F^l_k(x^n_k)x^l_k + G^l_k(x^n_k)v^l_k \\
y_k &= h_k(x^n_k) + H_k(x^n_k)x^l_k + e_k
\end{aligned}$$

The resulting algorithm is a mixture of particle filter steps and Kalman filter like steps. For the latter, the first equations above is interpreted as virtual measurement equations, and the resulting update step does not immediately fit a Kalman filter framework. The article [22] makes a more or less trivial re-formulation of the model above as

$$\begin{aligned}
x_{k+1} &= F^n_k(x^n_k)x_k + f_k(x^n_k) + G_k(x^n_k)v_k \\
y_k &= H_k(x^n_k)x_k + h_k(x^n_k) + e_k
\end{aligned}$$

This model is exactly on the same form as the model used in Kalman filter banks, where the non-linear part of the state vector, x^n_k, corresponds to the discrete mode of the system. This fact is exploited in [22], and an algorithm that has the same steps as a Kalman filter bank is presented, but where the mode pruning is replaced with stochastic re-sampling. The key advantage is that all updates are either pure Kalman filter measurement and time updates, or standard particle filter steps. This facilitates code reuse and object oriented implementations.

5.4.3 Particle Filtering with Signal Propagation Delays

An increasing trend in sensor networks is to use many cheap and low quality sensors to accomplish the tasks that were done in the past using few expensive and high-quality sensors. In such scenarios, the signal propagation delays between the target and the sensors start to become more and more important. This is especially the case when the target speed approaches the propagation speed of the signals (e.g., sound) in the propagation medium (air, in the case of sound).

A deterministic sampling based estimation algorithm was proposed from our group in the previous years in order to compensate for the unpredictable effects of propagation delays in the tracking filters. This year, the follow-up work in [63] generalizes the delay compensation framework we proposed earlier to particle filters.

5.4.4 Marginalized Particle Filters for Bayesian Estimation of Gaussian Noise

We suggest a marginalization approach for estimating the unknown parameters of process and measurement noises in general nonlinear state space models in [68]. Particle filter provides a general solution to the nonlinear filtering problem with arbitrarily accuracy. However, the curse of dimensionality prevents its application in cases where the state dimensionality is high. Furthermore, estimation of the stationary parameters is a known challenge in the particle filtering framework. The posterior densities of unknown mean and covariance of both process and measurement noises have the sufficient statistics which allows recursive analytical updating using the concept of conjugate prior distributions. The resulting marginalized particle filter improves other approaches in the literature in that it does neither require any extra states for the parameters, nor additional sampling steps. The resulting algorithm is illustrated on both a standard example and a navigation application based on odometry. The latter involves formulas for dead reckoning rotational speeds of two wheels with unknown radii.

5.4.5 Particle Filters with Dependent Noise

The theory and applications of the particle filter (PF) have developed tremendously during the past two decades. However, there appears to be no version of the PF readily applicable to the case of dependent process and measurement noises. This is in contrast to the Kalman filter, where the case of correlated noise is a standard modification. This noise dependency arises quite naturally in many practical problems of interest. Further, the fact that sampling continuous time models leads to dependent noise processes is an often neglected fact in literature. We develop a PF framework with this noise dependency in [50]. The corresponding optimal proposal distribution was derived, and the two most common approximations (prior and likelihood, respectively) were also stated. The special case of additive Gaussian noise processes was studied in detail, and the common Bootstrap/SIR PF was modified by a new prediction step.

5.4.6 Decentralization of Particle Filters

In the work [38], a new PF which we refer to as the decentralized PF (DPF) is proposed. By first decomposing the state into two parts, the DPF splits the filtering problem into two nested sub-problems and then handles the two nested sub-problems using PFs. The DPF has an advantage over the regular PF that the DPF can increase the level of parallelism of the PF. In particular, part of the resampling in the DPF bears a parallel structure and thus can be implemented in parallel. The parallel structure of the DPF is created by decomposing the state space, differing from the parallel structure of the distributed PFs which is created by dividing the sample space. This difference results in a couple of unique features of the DPF in contrast with the existing distributed PFs.

5.5 Target Tracking

5.5.1 A GM-PHD Filter for Extended Target Tracking

In classic target tracking, it is often assumed that each target causes at most one measurement per time step. However, with many modern sensors, e.g., cameras, laser range sensors, and automotive radar, the single measurement assumption does not apply. Instead, the targets occupy multiple resolution cells of the sensor, and thus cause multiple measurements per time step. Such targets are called extended targets.

Finite set statistics (FISST) provides a rigorous framework for multiple target tracking. Using FISST, the probability hypothesis density (PHD) filter can be derived, giving a framework for propagation of the first order moment of a random set. An implementation of a Gaussian Mixture PHD filter for extended target tracking was presented in [48]. The implemented filter requires a summation over all possible partitions of the measurement set, an operation which quickly becomes intractable as the size of the measurement set grows. To remedy the problem, a partitioning function is proposed that reduces the number of partitions that have to be considered by several orders of magnitude. The implemented extended target tracking framework can efficiently track multiple targets that each produce a Poisson distributed number of measurements. In cluttered sets of measurements the target cardinality (i.e., the number of targets) is correctly estimated, with the exception of when targets are spatially very close.

5.5.2 Magnetometers for Tracking Metallic Targets

Tracking and classification of vehicles are primary concerns in intelligent transportation and security systems. During the spring, the use of magnetometers for such applications was investigated in the master's thesis [152]. Early results from that work resulted in a conference contribution [72].

5.5.3 Combined PMF and PF for Target Tracking

The paper [65] presents a combined point mass filter (PMF) and particle filter (PF), which utilizes the support of the PMF and the high particle density in the PF close to the current estimate. The result is a filter robust to unexpected process events but still with low error covariance. This filter is especially useful for target tracking applications, where target maneuvers suddenly can change unpredictably.

5.5.4 Multiple Target Tracking with Acoustic Power Measurements

Multiple target tracking using acoustic power measurements obtained from an acoustic sensor network poses problems that are quite unconventional for target tracking. Since the sensors are superpositional, the classical notion of data association becomes irrelevant. In the work [64] we show how one can achieve an acceptable multiple target tracking performance for this problem using a novel concept called emitted power density (EPD) which is an aggregate information state that holds the emitted power distribution of all targets in the scene over the target state space. We propose a Gaussian process based representation for estimating the EPDs using Kalman filter formulas, which results in a recursive EPD-filter that is based on the discretization of the position component of the target state space. The results are illustrated on a real data scenario, where experiments are done with two targets constrained to a road segment.

Chapter 6

Robotics

6.1 Introduction

The research within the robotics area is to a large extent carried out in close cooperation with ABB Robotics and ABB Corporate Research. From 2008 the collaboration is carried out within the Industry Excellence Center LINK-SIC (Linköping Center for Sensor Informatics and Control) supported by VINNOVA. The overall aim of the center is to generate results that are of both high scientific quality and industrial relevance.

6.2 Modeling, Identification, and Control

The performance requirements in terms of cycle time and accuracy of modern industrial robots require carefully designed control methods based on accurate dynamical models. Due to a desire to reduce cost and weight, each new robot generation offers new challenges since the robots contain more of mechanical elasticities. The PhD thesis by Stig Moberg, [1], addresses the entire chain from physical modeling and parameter estimation to feedforward control and robust feedback.

The thesis deals with different aspects of modeling and control of flexible, i.e., elastic, manipulators. For an accurate description of a modern industrial manipulator, this thesis shows that the traditional flexible joint model, described in literature, is not sufficient. An improved model where the elasticity is described by a number of localized multidimensional spring-damper pairs is therefore proposed. This model is called the extended flexible joint

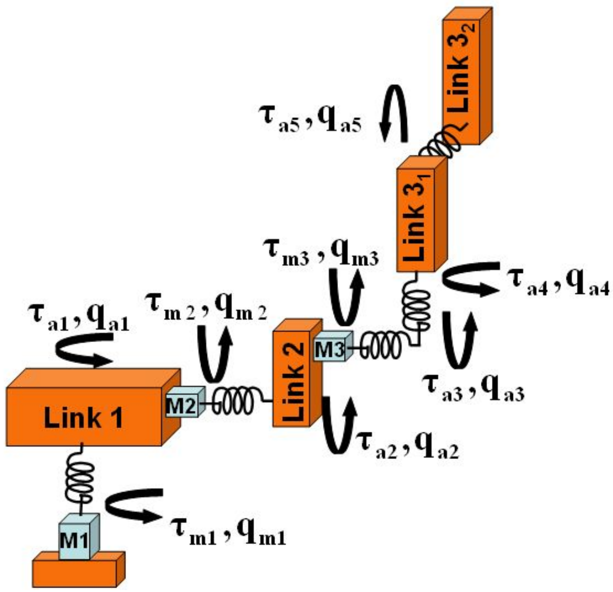


Figure 6.1: An extended flexible joint dynamic model with eight degrees of freedom.

model. An example of such a model structure with eight degrees of freedom is shown in Figure 6.1.

The main contributions of the work are the design and analysis of identification methods, and of inverse dynamics control methods, for the extended flexible joint model. The proposed identification method is a frequency-domain non-linear gray-box method, which is evaluated by the identification of a modern six-axes robot manipulator. The identified model gives a good description of the global behavior of this robot. The inverse dynamics problem is discussed, and a solution methodology is proposed. This methodology is based on the solution of a differential algebraic equation (DAE). The inverse dynamics solution is then used for feedforward control of both a simulated manipulator and of a real robot manipulator. The last part of the work concerns feedback control. First, a model-based nonlinear feedback control (feedback linearization) is evaluated and compared to a model-based feedforward control algorithm. Finally, two benchmark problems for robust feedback control of a flexible manipulator are presented and some proposed solutions are analyzed.

6.3 Trajectory Generation and Time Optimal Control

To maximize the productivity in modern production plants, the cycle time in the robot cells is often a limiting factor. Therefore time-optimal motion planning applied to robotic manipulators is of significant importance in real applications. For an optimization method to be useful there are a number of requirements that have to be met. Firstly the solution, the time optimal trajectory, must be possible to compute in a short time, preferably in real time. Secondly, the optimization problem formulation must have a high degree of flexibility, which means that it must be easy to add new constraints and the constraints must be possible to parameterize in a general way. Of equal importance is that the optimization uses realistic constraints, considering both the user's demands on the tool velocity, as well as the internal robot constraints. In [77] previous results in literature on time optimal convex optimization for a predefined path are extended to cover speed dependent constraints, such as viscous friction in the model. In Figure 6.2 an example is shown to illustrate the difference in the torque utilization, using constant torque constraint, and speed dependent torque constraint. The speed dependent constraint makes it possible to get higher torque at lower speed and, at the same time, increase the maximum speed compared to the constant torque constraint approach. In [77] it is shown how the speed dependent constraints should be added in order to keep the convexity of the overall problem. A method to, conservatively, approximate the linear speed dependent constraints by a convex constraint is also proposed. A numerical example is provided where the resulting performance difference is illustrated in terms of decreased cycle time.

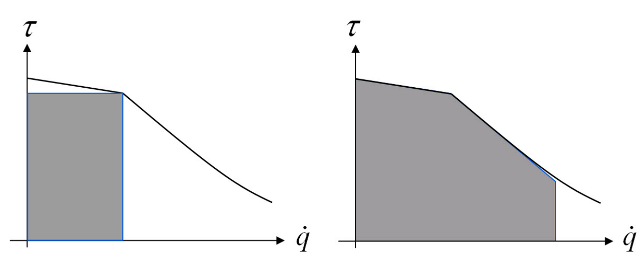


Figure 6.2: Resulting torque constraints when considering constant torque (left), and speed dependent torque (right).

6.4 Sensor Fusion

One consequence of the increased mechanical flexibility of modern industrial robots is a need to develop methods to estimate the position, orientation, speed, etc., of the robot tool. It is therefore natural to apply sensor fusion methods to industrial robots, and this is for several reasons a very challenging task. First, the dynamic model of an industrial robot is very complex, and that will make sensor fusion algorithms very computationally demanding, and second, the models will contain a large number of model parameters, which unavoidably are subject to uncertainty. These aspects lead to the problem of designing and tuning sensor fusion algorithms of realistic complexity that are able to generate estimates of sufficient accuracy. One aspect of the tuning problem is studied in [78], where a variant of the expectation maximization (EM) algorithm is used and iteratively estimates the unobserved state sequence and Q based on the observations of the process. The extended Kalman smoother (EKS) is the instrument to find the unobserved state sequence. The contribution fills a gap in literature, where previously only the linear Kalman smoother and particle smoother have been applied. The algorithm will be important for future industrial robots with more flexible structures, where the particle smoother cannot be applied due to the high state dimension. The proposed method is compared to two alternative methods on a simulated robot.

6.5 Iterative Learning Control

Since an industrial robot typically carries out operations repeatedly, this can be utilized in order to iteratively improve the accuracy of the control system. This control method, denoted iterative learning control (ILC), has been an active research area within the group for several years.

The interest during the recent years has been concentrated to ILC applied to robots containing mechanical flexibilities. The large challenge in such a case is that the controlled variables are different from the measured variables. In standard industrial robots the controlled variables are the position and the orientation of the tool, while the measured variables are the angles of the motors that generate the motion. This situation implies that good performance when studying the measured variables does not necessarily imply good performance of the controlled variables.

One approach to handle this problem is to estimate the position and orientation of the tool and use the estimated variables in the ILC algorithm. This idea has been implemented and evaluated in simulation examples in previous publications, and it has now been generalized by formulating av framework for observer-based ILC, presented in [73]. The framework can be used to analyze the control performance using different types of ILC algorithms and different ways to estimate the controlled variables, also including additional sensors. ILC using estimated signals has also been implemented and evaluated in experiments using the so called Gantry-Tau parallel kinematic robot structure. The experiments, presented in [122], show that there is a large potential in using estimated variables in ILC.

By definition an ILC algorithm operates over finite time intervals, and since it often involves non causal filtering operations it is important to handle the boundary effects in an appropriate way when implementing the algorithm. In [123] some alternative ways to handle boundary effects are presented, and it is found that they can have a large impact on the algorithm performance and even affect the stability properties.

6.6 Robot Diagnosis

Industrial robots are often used in large and complex production systems where productivity and reliability is of extreme importance. It is therefore critical to be able to detect if the performance of the components of the production system, in this case the industrial robot, starts to deteriorate and if there is risk for mechanical failures. The gearboxes are critical components for the performance of a robot and it is hence important to monitor their performance. The performance and condition of a gearbox can in many cases be related to friction, and it is of interest to be able to model the friction. In this work the aim is to extend traditional static friction models, where the friction torque depends on velocity only, by including also load torque and temperature. Based on extensive experiments and data collection, an extended friction model has been derived. Details concerning the modeling procedure are given in [37] and it results in a model with the structure

$$\begin{aligned} \tau_f(\dot{\varphi}_m, \tau_m, T) &= (F_{c,0} + F_{c,\tau_m} \mid \tau_m \mid) + F_{s,\tau_m} \mid \tau_m \mid e^{-\left|\frac{\dot{\varphi}_m}{\dot{\varphi}_{s,\tau_m}}\right|^{1.3}} \\ &+ (F_{s,0} + F_{s,T}T) \mid \tau_m \mid e^{-\left|\frac{\dot{\varphi}_m}{\dot{\varphi}_{s,0}+\dot{\varphi}_{s,T}T}\right|^{1.3}} + (F_{v,0} + F_{v,T}e^{\frac{-T}{T_{V_0}}})\dot{\varphi}_m \end{aligned}$$

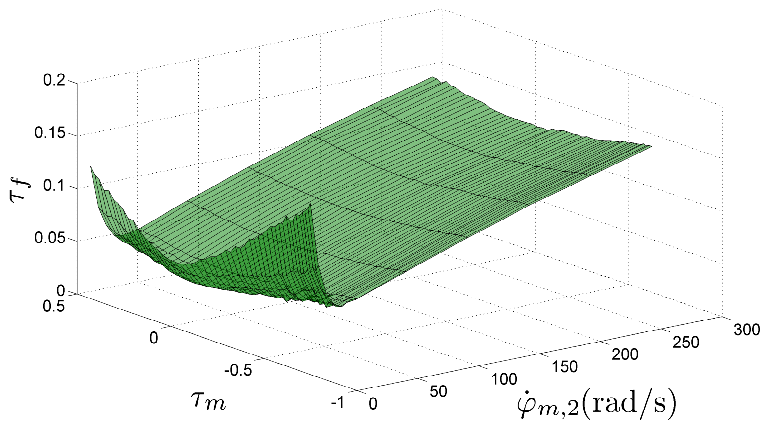


Figure 6.3: Friction as function of angular velocity and load torque.

where τ_m and T denote load torque and temperature respectively. Figure 6.3 shows how the friction torque depends on the angular velocity and the load torque for one particular temperature. A number of other aspects of the problem are discussed in [37].

In [85] a statistical method is developed for estimation of wear in the gearbox, using the extended friction model above. In practice the temperature is not measured and in the method this is handled by assuming a statistical distribution of the temperature.

Chapter 7

Optimization for Control

The research in optimization for control is currently focused on optimization algorithms for robust control, model predictive control, and model reduction.

7.1 Optimization Algorithms for Robust Control

In this project we study how to efficiently solve optimization problems for robust control.

7.1.1 Structure Exploitation in Semidefinite Programming for Control

In the Licentiate thesis by Rikard Falkeborn, [3], two ways to exploit structure in semidefinite programming for control is investigated.

One is related to semi-definite programs (SDPs) derived from the Kalman-Yakubovich-Popov (KYP) lemma. There are several applications for such SDPs in control and signal processing, e.g., filter design, robust control analysis, Lyapunov function search, etc. In industrial applications the optimization problems often get so large that standard SDP solvers cannot handle them. It is shown that dual decomposition can be useful for certain applications. One such application that is considered in more detail in the thesis is mixed H_2/H_∞-design.

The second approach exploits the fact that many SDPs in control theory involve matrix variables, i.e., the decision variables in the optimization problem enter in a very particular manner. By using this fact, the compilation of the linear system to determine the search direction in an SDP solver can be sped up significantly. The method is implemented as an add-on to the public SDP solver SDPT3, is completely transparent to the user, and has shown gains of up to an order of magnitude on standard problems in control [43].

7.1.2 Robust Finite-Frequency H_2-Analysis

Finite frequency H_2 analysis is relevant to a number of problems in which a prior information is available on the frequency domain of interest. This work addresses the problem of analysing robust frequency H_2 performance of systems with structured uncertainties. An upper bound on this measure is provided by exploiting convex optimization tools for robustness analysis and the notion of finite-frequency Gramians. An application to a comfort analysis problem for an aircraft aeroelastic model is also investigated in [107, 58].

7.1.3 Polytopic Differential Inclusions

Polytopic differential inclusions is a common way to represent uncertainty in dynamical systems. These type of systems can be analysed with SDPs. One way to solve these SDPs in an efficient way is to use an infeasible interior point method where the search directions are not computed exactly, see [20].

7.2 Model Predictive Control

Model predictive control (MPC) is based on solving optimization problems on-line in order to perform the best possible action on controlled systems. For some systems, it is not tractable to run a full-fledged optimization algorithm in real-time, typically due to computational resources. Explicit MPC is a recent popular approach to overcome this by computing the optimal control policy off-line, using multiparametric programming. The optimal policy is in the case of piecewise affine systems a piecewise affine control law, which thus should be used on-line. Unfortunately, this piecewise affine function can easily become very complex, thus rendering also the explicit MPC approach intractable. In [52], it is shown how the complex piecewise affine control law can be approximated using low-complexity polynomial expressions. The approximation is efficiently derived using linear programming.

MPC can be applied to linear as well as to nonlinear systems. A special case of nonlinear systems that has received an increased attention in the MPC community the past 10 years is hybrid systems. Hybrid systems are systems where continuous dynamics interact with logic. Due to the logic in the system, the MPC optimization problem becomes significantly more challenging compared to MPC for linear systems. In order to solve these optimization problems a branch and bound method is used. In this method upper and lower bounds of the optimal objective function value are computed. The performance of the algorithm is highly dependent on how close these upper and lower bounds are compared to the true optimal objective function value and, of course, how fast these computations can be performed. In [7] semidefinite programming (SDP) relaxations are investigated as means for computing the lower bounds (relaxation). In that work, different relaxations applicable to the hybrid MPC application are compared and it is studied how these can be computed efficiently.

7.2.1 Applications

In [70] an application of MPC to speed tracking of a linear induction motor is presented. The key to an efficient implementation is to carry out the optimization for the finite alphabet controller by enumeration.

7.3 Model Reduction

Model reduction focuses on how to find lower-order models or controllers for more complex systems. These kind of problems are normally nonconvex and various optimization techniques can be used.

In [75] an approach to low order H_∞ control is presented that is based on formulating the constraint on the maximum order of the system as a polynomial or rational criterion. By using the fact that this function is non-negative on the feasible set, the problem is reformulated as an optimization problem where the nonconvex criterion function is minimized over a convex set defined by linear matrix inequalities (LMIs). To solve this optimization problem, a method based on a primal-dual framework is proposed. The method has been evaluated on several problems and compared with a well-known method found in the literature. These results are also presented in [33]. In [76], numerical results from a modified version of the method discussed in [75] is presented.

In the Licentiate thesis by Daniel Petersson, [4], methods for identifying linear parameter-varying (LPV) state-space models and for finding low-order LPV controllers for LPV state-space models that are based on model reduction techniques are presented. Results can also be found in [113, 114]. The emphasis is on derivation of computationally efficient schemes to optimize system-relevant performance measures of the approximation quality. Problem specific regularization terms are derived to make the solutions more robust to uncertainties in data, see [66].

Appendix A

Personnel

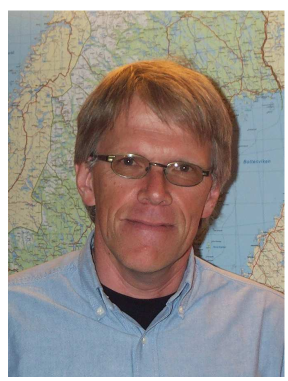
Lennart Ljung is Professor and head of the Division of Automatic Control since 1976. He was born in 1946 and received his Ph. D. in Automatic Control from Lund Institute of Technology in 1974. He is a member of the Royal Swedish Academy of Engineering Sciences (IVA) and the Royal Swedish Academy of Sciences (KVA). He is an honorary member of the Hungarian Academy of Engineering, and a Foreign Associate of the US National Academy of Engineering (NAE). He is also an IEEE Fellow and an IFAC Advisor, and associate editor of several journals. He has received honorary doctor's degrees from the Baltic State Technical University in S:t Petersburg, Russia (1996), from Uppsala University, Uppsala, Sweden (1998), from l'Université de Technologie de Troyes, France (2004), from the Katholieke Universiteit in Leuven, Belgium (2004) and from Helsinki Institute of Technology (2008). In 2002 he received the Quazza medal from IFAC, in 2003 the Hendrik W. Bode Lecture Prize from the IEEE Control Systems Society, and in 2007 the IEEE Control Systems Field Award.

E-mail: ljung@isy.liu.se

Torkel Glad is Professor of Nonlinear Control Systems at the Division of Automatic Control. He was born in Lund, Sweden in 1947. He received his M. Sc. degree in Engineering Physics in 1970 and the Ph. D. degree in Automatic Control in 1976, both from the Lund Institute of Technology, Lund, Sweden. Since 1988 he is Professor in the control group. His research interests include nonlinear systems, algebraic aspects of system theory, optimal control and applications to systems biology.

E-mail: torkel@isy.liu.se

Svante Gunnarsson is Professor at the Division of Automatic Control, and was born in 1959. He received his M. Sc. in 1983, his Techn. Lic. in 1986 and his Ph. D. in 1988 all from Linköping University. From 1989 he was Associate Professor at the department, and from 2002 Professor. His research interests are robotics, system identification, and iterative learning control.

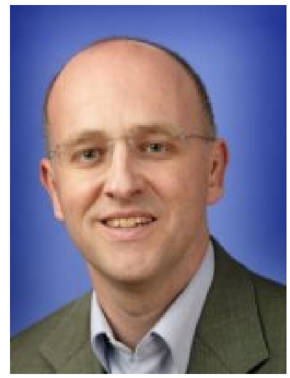


E-mail: svante@isy.liu.se

Fredrik Gustafsson is Professor in Sensor Informatics at the Division of Automatic Control since 2005. He was born in 1964 and he received the M. Sc. degree in Electrical Engineering 1988 and the Ph. D. degree in Automatic Control, 1992, both from Linköping University. During 1992-1999 he held various positions in Automatic Control, and in 1999 he got a professorship in Communication Systems. His research interests are in statistical signal processing, adaptive filtering and change detection, with applications to vehicular, airborne, communication and audio systems. He was associate editor for IEEE Transactions of Signal Processing 2000-2006 and is currently associate editor for EURASIP Journal on Applied Signal Processing and International Journal of Navigation and Observation.

E-mail: fredrik@isy.liu.se

Anders Hansson is Professor at the Division of Automatic Control, and he was born in Trelleborg, Sweden, in 1964. He received the M. Sc. 1989, Techn. Lic. in 1991, and the Ph. D. in 1995, all from Lund University, Lund, Sweden. From 1995 to 1998 he was employed by the Information Systems Lab, Stanford University. From 1998 to 2000 he was Associate Professor at Automatic Control, KTH, Stockholm. From 2001 he was an Associate Professor at the Division of Automatic Control, Linköping University. From 2006 he is Professor at the same division. He was associate editor of IEEE Transactions on Automatic Control 2006 – 2007. He is also a member of the EUCA Council from 2009, and of Technical Committee on Systems with Uncertainty of the IEEE Control Systems Society from 2009. His research interests are applications of optimization to control and signal processing.



E-mail: hansson@isy.liu.se

Mille Millnert is Professor at the Division of Automatic Control. He was born in 1952 and received his M. Sc. in 1977 and his Ph. D. in Automatic Control 1982 from Linköping University. His research interests are model based signal processing, parameter estimation and the combination of numerical and symbolical techniques in signal processing and control. From July 1996 he was Dean of the School of Engineering at Linköping University and from October 2003 he is President of Linköping University.

E-mail: mille@isy.liu.se

Anders Helmersson is Adjunct Professor at the Division of Automatic Control. He was born in 1957. In 1981, he received his M. Sc. in Applied Physics at Lund Institute of Technology. He has been with Saab Space since 1984. In 1993 he joined the Division of Automatic Control where he received his Ph. D. in 1995. His research interest is mainly in robust control and gain scheduling. He is currently employed by RUAG Aerospace Sweden AB (formerly Saab Space AB).

E-mail: andersh@isy.liu.se

Alf Isaksson is Adjunct Professor at the Division of Automatic Control. He was born in 1959, and he received his M. Sc. in 1983, his Techn. Lic. in 1986 and his Ph. D. in 1988, all from Linköping University. He is currently employed by ABB AB.

E-mail: alf@isy.liu.se

Mikael Norrlöf is Adjunct Professor at the Division of Automatic Control. He was born in Karlstad, 1971. He received his M. Sc. in Computer Science and Engineering 1996, his Techn. Lic. in 1998, his Ph. D. in 2000 and he became Docent in 2005, all at Linköping University. His current research interests include iterative learning control, robot modeling and control, trajectory generation, and sensor fusion applications. He also works as Principal Research and Development Engineer at ABB in Västerås.

E-mail: mino@isy.liu.se

Martin Enqvist is Associate Professor at the Division of Automatic Control. He was born in 1976 and received his M. Sc. in Applied Physics and Electrical Engineering in 2000, his Techn. Lic. in 2003 and his Ph. D. in 2005 all at Linköping University. During 2006, he was employed as a Postdoctoral Associate at Vrije Universiteit Brussel in Belgium. His research interests are mainly within the area of system identification.

E-mail: maren@isy.liu.se

Inger Klein is Associate Professor at the Division of Automatic Control. She was born in 1964. She received her M. Sc. in 1987, her Techn. Lic. in 1990, and her Ph. D. in 1993, all from Linköping University. Her research interest is diagnosis, fault detection and fault isolation, in particular for discrete event systems.

E-mail: inger@isy.liu.se

Thomas Schön is Associate Professor at the Division of Automatic Control. He was born in 1977. He received the Ph. D. degree in Automatic Control in 2006, the M. Sc. degree in Applied Physics and Electrical Engineering in 2001 and the B. Sc. degree in Business Administration and Economics in 2001, all from Linköping University. He has held visiting positions at the University of Cambridge (UK) and the University of Newcastle (Australia). His research interests are mainly within the areas of signal processing, machine learning and system identification and robotics, with applications mainly to the automotive and the aerospace industry.

E-mail: schon@isy.liu.se

Fredrik Gunnarsson is Visiting Associate Professor at the Division of Automatic Control. He was born in 1971. He received his M. Sc. in Applied Physics and Electrical Engineering in 1996 his Techn. Lic. in 1998 and his Ph. D. in 2000, all at Linköping University. His current research interests include control theory and signal processing aspects of wireless communications. He also works as a Senior Research Engineer at Ericsson Research.

E-mail: fred@isy.liu.se

Daniel Axehill is Assistant Professor at the Division of Automatic Control. He was born in 1978. He received his M. Sc. in Applied Physics and Electrical Engineering in 2003, his Techn. Lic. in 2005, and his Ph. D. in 2008 all from Linköping University. From January 2009 until November 2010, he was holding a Postdoctoral Associate position at the automatic control group at ETH Zürich. His main research interest is optimization algorithms for control.

E-mail: daniel@isy.liu.se

Gustaf Hendeby is Assistant Professor at the Division of Automatic Control. He was born in 1978. He received his M. Sc. in Applied Physics and Electrical Engineering in 2003, his Techn. Lic. in 2005, and his Ph. D. 2008 all from Linköping University. His main research interests are in signal processing and sensor fusion.

E-mail: hendeby@isy.liu.se

Johan Löfberg is the Director of Studies and Assistant Professor at the Division of Automatic Control, and he was born in 1974. He received his M. Sc. in Mechanical Engineering in 1998, his Techn. Lic. in 2001 and his PhD in 2003, all at Linköping University. During 2003 - 2006 he was employed as a Postdoctoral Associate at ETH, Zürich. His research interests are mainly within the area of optimization and model predictive control.

E-mail: johanl@isy.liu.se

Umut Orguner is Assistant Professor at the Division of Automatic Control. He was born in 1977. He received B. Sc., M. Sc. and Ph. D. degrees all in Electrical Engineering from Middle East Technical University, Ankara, Turkey in 1999, 2002 and 2006, respectively. Between 1999 and 2007, he was with the Department of Electrical and Electronics Engineering at the same university as a teaching and research assistant. His research interests include estimation theory, multiple-model estimation, target tracking and information fusion.

E-mail: umut@isy.liu.se

Johan Sjöberg is Assistant Professor at the Division of Automatic Control. He was born in 1978. He received his M. Sc. in Applied Physics and Electrical Engineering in 2003, his Techn. Lic. in 2006 and his Ph. D. in 2008 all from Linköping University. His main research interest is in nonlinear optimal control.

E-mail: johans@isy.liu.se

Henrik Tidefelt is Assistant Professor at the Division of Automatic Control. He was born in 1978. He received his M. Sc. in Applied Physics and Electrical Engineering in 2004, his Techn. Lic. in 2007, and his Ph. D. in 2009, all from Linköping University. His main interest is uncertainty in differential-algebraic equations.

E-mail: tidefelt@isy.liu.se

David Törnqvist is Assistant Professor at the Division of Automatic Control. He was born in 1979. He received his M. Sc. in Communication and Transport Engineering in 2003, his Techn. Lic. in 2006 and his Ph. D. in 2008 all from Linköping University. His main research interests are in signal processing and sensor fusion.

E-mail: tornqvist@isy.liu.se

Ragnar Wallin is Assistant Professor at the Division of Automatic Control. He was born in 1962. He received his M. Sc. in Electrical Engineering in 1998 and his Techn. Lic. in 2000 both from the Royal Institute of Technology (KTH), Stockholm and his Ph. D. in 2005 at Linköping University. His research interests are in optimization algorithms, mainly for gain scheduling applications.

E-mail: ragnarw@isy.liu.se

Erik Wernholt is Assistant Professor at the Division of Automatic Control. He was born in 1975. He received his M. Sc. in Applied Physics and Electrical Engineering in 2001, his Techn. Lic. in 2004 and his Ph. D. in 2007, all at Linköping University. His research interests are in system identification, mainly for industrial robots.

E-mail: erikw@isy.liu.se

Tianshi Chen is a Postdoctoral Associate at the Division of Automatic Control. He was born in 1978. He received his B. Sc. and M. Sc. degree from Harbin Institute of Technology, Harbin, China in 2001 and 2005, respectively. He received his Ph. D. from The Chinese University of Hong Kong, Hong Kong, China in 2008. Between August 2005 and December 2008, he was with the Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong as a Teaching Assistant and Research Assistant.

E-mail: tschen@isy.liu.se

Mehmet B. Guldogan is a Postdoctoral Associate at the Division of Automatic Control. He was born in 1980. He received his B. Sc., M. Sc. and Ph. D. degrees all in Electrical and Electronics Engineering from Bilkent University, Ankara, Turkey in 2003, 2006 and 2010, respectively. Between 2007 and 2010, he was with the Department of Electrical and Electronics Engineering at the same university as a teaching and research assistant. His research interests include array signal processing, channel estimation, computational swarm intelligence and target tracking.

E-mail: bguldogan@isy.liu.se

Saikat Saha is a Postdoctoral Associate at the Division of Automatic Control. He was born in 1974. He received his M. Sc. from the Indian Institute of Science in 2003 and Ph. D. from University of Twente, The Netherlands in 2009. His research interests include statistical signal processing, sensor fusion, system identification and computational finance.

E-mail: saha@isy.liu.se

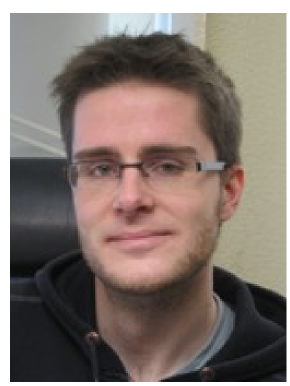
Jean Thomas is a Postdoctoral Associate at the Division of Automatic Control. He was born in Minia, Egypt, in 1969. He received his B. Sc. degree in 1991 in Electricial Engineering from Minia University, Egypt, and his M. Sc. degree in Process Control in 1997 from Eindhoven Technical University, The Netherlands. In 2004 he received his Ph. D. degree in Automatic Control from Supelec, France. Since 2005, he is an Associate Professor in Beni-Suef University, Egypt. His research interests include hybrid systems, predictive control and robust control.

E-mail: jean@isy.liu.se

Emre Özkan is a Postdoctoral Associate at the Division of Automatic Control. He was born in 1980. He received B. Sc. and Ph. D. degrees both in Electrical Engineering from Middle East Technical University, Ankara, Turkey in 2002 and 2009, respectively. Between 2002 and 2009, he was at the Department of Electrical and Electronics Engineering at the same university as a teaching and research assistant. His research interests include estimation theory, parameter estimation, target tracking and information fusion.

E-mail: emre@isy.liu.se

Daniel Ankelhed is a Ph. D. student at the Division of Automatic Control. He was born in 1980. He received his M. Sc. in Applied Physics and Electrical Engineering in 2005 and his Techn. Lic. in 2009, both from Linköping University. His main research interest is synthesis of low order H_∞ controllers.



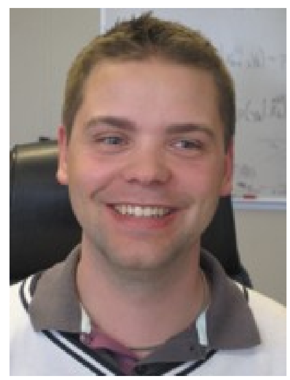
E-mail: ankelhed@isy.liu.se

Tohid Ardeshiri is a Ph. D. student at the Division of Automatic Control. He was born in 1980. He received his B. Sc. in 2003 in Mechanical Engineering from Sharif University of Technology and his M. Sc. in 2005 in Automotive Engineering from Chalmers, Göteborg, Sweden.

E-mail: tohid.ardeshiri@isy.liu.se

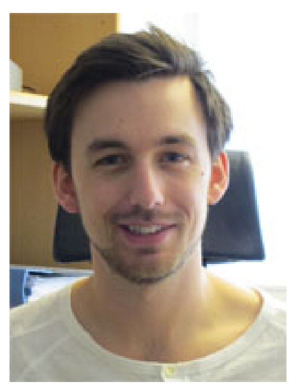
Patrik Axelsson is a Ph. D. student at the Division of Automatic Control. He was born in 1985. He received his M. Sc. in 2009 in Applied Physics and Electrical Engineering from Linköping University.

E-mail: axelsson@isy.liu.se



Jonas Callmer is a Ph. D. student at the Division of Automatic Control. He was born in 1981. He received his M. Sc. in 2008 in Applied Physics and Electrical Engineering from Linköping University.

E-mail: callmer@isy.liu.se



André Carvalho Bittencourt is a Ph. D. student at the Division of Automatic Control. He was born in 1984. He received his B. Sc. in 2009 in Automatic Control from Federal University of Santa Catarina, Brazil.

E-mail: andrecb@isy.liu.se

Rikard Falkeborn is a Ph. D. student at the Division of Automatic Control. He was born in 1982. He received his M. Sc. in 2006 in Applied Physics and Electrical Engineering and his Techn. Lic. in 2010, both from Linköping University.

E-mail: falkeborn@isy.liu.se

Karl Granström is a Ph. D. student at the Division of Automatic Control. He was born in 1981. He received his M. Sc. in 2008 in Applied Physics and Electrical Engineering from Linköping University.

E-mail: karl@isy.liu.se

Jeroen Hol is a Ph. D. student at the Division of Automatic Control. He was born in 1981. He received his M. Sc. in 2005 from Twente University, Enschede, The Netherlands, and his Techn. Lic. in 2008 from Linköping University.

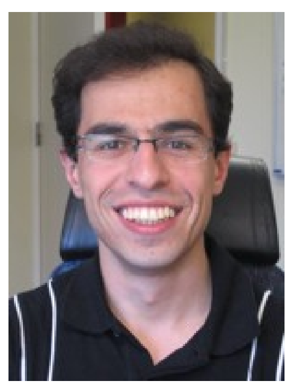
E-mail: hol@isy.liu.se

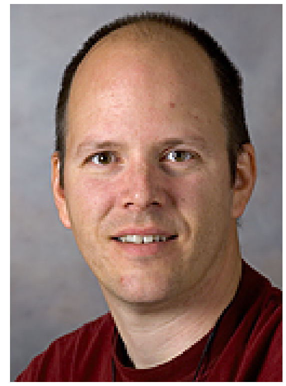
Ylva Jung is a Ph. D. student at the Division of Automatic Control. She was born in 1984. She received her M. Sc. in 2009 in Applied Physics and Electrical Engineering International from Linköping University.

E-mail: ylvju@isy.liu.se

Sina Khoshfetrat Pakazad is a Ph. D. student at the Division of Automatic Control. He was born in 1985 and received his M. Sc. in 2009 from Chalmers University of Technology, Göteborg, Sweden.

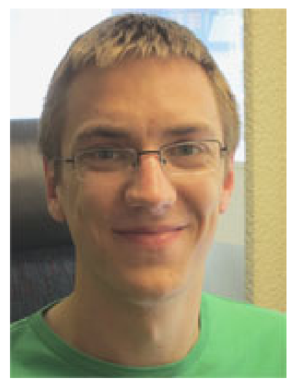
E-mail: sina.kh.pa@isy.liu.se





Roger Larsson is a Ph. D. student at the Division of Automatic Control. He was born in 1968. He received his M. Sc. in 1996 in Vehicle Engineering from Royal Institute of Technology in Stockholm, Sweden. He is employed by Saab AB.

E-mail: roglar@isy.liu.se



Fredrik Lindsten is a Ph. D. student at the Division of Automatic Control. He was born in 1984. He received his M. Sc. in 2008 in Applied Physics and Electrical Engineering from Linköping University.

E-mail: lindsten@isy.liu.se

Christian Lundquist is a Ph. D. student at the Division of Automatic Control. He was born in 1978. He received his M. Sc. in 2003 in Automation and Mechatronics Engineering from Chalmers, Göteborg, and his Techn. Lic. in 2009 from Linköping University.

E-mail: lundquist@isy.liu.se

Christian Lyzell is a Ph. D. student at the Division of Automatic Control. He was born in 1980. He received his M. Sc. in 2007 in Applied Physics and Electrical Engineering and his Techn. Lic. in 2009, both from Linköping University.

E-mail: lyzell@isy.liu.se

Stig Moberg is a Ph. D. student at the Division of Automatic Control. He was born in 1962. In 1986, he received his M. Sc. in Engineering Physics from Uppsala University. He received his Techn. Lic. in 2007, and his Ph. D. in 2010,both from Linköping University. He is currently employed as Senior Principal Engineer by ABB Robotics and his research interests are in the area of industrial robot control.

E-mail: stig@isy.liu.se

Henrik Ohlsson is a Ph. D. student at the Division of Automatic Control. He was born in 1981. He received his M. Sc. in Applied Physics and Electrical Engineering in 2006, his Techn. Lic. in 2008, and his Ph. D. in 2010 all from Linköping University. His main research interests are system identification and machine learning.

E-mail: ohlsson@isy.liu.se

Daniel Petersson is a Ph. D. student at the Division of Automatic Control. He was born in 1981. He received his M. Sc. in Applied Physics and Electrical Engineering in 2006 and his Techn. Lic. in 2010, both at Linköping University.

E-mail: petersson@isy.liu.se

Peter Rosander is a Ph. D. student at the Division of Automatic Control. He was born in 1984. He received his M. Sc. in 2009 in Applied Physics and Electrical Engineering from Linköping University.

E-mail: rosander@isy.liu.se

Michael Roth is a Ph. D. student at the Division of Automatic Control since November 2010. He received his academic degree (Diplom-Ingenieur) in Electrical Engineering with a focus on automatic control from Technische Universität Berlin, Germany. In 2009, he visited the Scottish Centre for Innovation in Spinal Cord Injury where he was working on the application of system identification algorithms in spinal cord research.

E-mail: roth@isy.liu.se

Zoran Sjanic is a Ph. D. student at the Division of Automatic Control. He was born in 1975. He received his M. Sc. in 2002 in Computer Science and Engineering from Linköping University. He is employed by Saab AB.

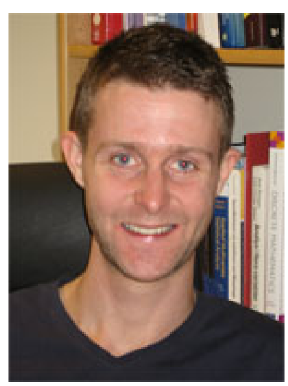
E-mail: zoran@isy.liu.se

Per Skoglar is a Ph. D. student at the Division of Automatic Control. He was born in 1977. He received his M. Sc. in Applied Physics and Electrical Engineering in 2002 and his Techn. Lic. in 2009, both from Linköping University.

E-mail: skoglar@isy.liu.se

Martin Skoglund is a Ph. D. student at the Division of Automatic Control. He was born in 1981. He received his M. Sc. in 2008 in Applied Physics and Electrical Engineering from Linköping University.

E-mail: ms@isy.liu.se



Lubos Vaci is a Ph. D. student at the Division of Automatic Control.

E-mail: lubos@isy.liu.se

Niklas Wahlström is a Ph. D. student at the Division of Automatic Control. He was born in 1984. He received his M. Sc. in Applied Physics and Electrical Engineering International in 2010 from Linköping University.

E-mail: nikwa@isy.liu.se

Johanna Wallén is a Ph. D. student at the Division of Automatic Control. She was born in 1979. She received her M. Sc. in Applied Physics and Electrical Engineering in 2004 and her Techn. Lic. in 2008, both from Linköping University. Current research interest is iterative learning control, especially in combination with additional sensors.

E-mail: johanna@isy.liu.se

Sören Hansson is employed as Research Engineer at the Division of Automatic Control on a part time basis, where he is responsible for the laboratory equipment.

E-mail: sorha@isy.liu.se

Åsa Karmelind is Coordinator for the Division of Automatic Control.

E-mail: karasa@isy.liu.se

Ulla Salaneck is Coordinator for the Division of Automatic Control.

E-mail: ulla@isy.liu.se

Visitors

Michel Verhaegen Delft University of Technology, Netherlands, visited the division on April 14-15.

Shankar Sastry University of California at Berkeley, USA, visited the division on April 27.

Roy S. Smith University of California, Santa Barbara, USA, visited the division on May 5.

Claire J. Tomlin Stanford University, USA, visited the division on May 25.

George Theodorakopoulos EPFL, Lausanne, Switzerland, visited the division on June 15.

Appendix B

Courses

B.1 Undergraduate Courses

M. Sc. (civ.ing.)-program

- *Automatic Control* (Reglerteknik) The basic control course given for all engineering programs. *Contents*: The feedback concept, PID-controllers, Frequency domain design techniques, Sensitivity and robustness, State space models and state feedback controllers, Observers.

  M Mechanical Engineering. 100 participants. Lecturer: Johan Löfberg.

  Y, D Applied Physics and Electrical Engineering and Computer Engineering. 130 participants. Lecturer: Torkel Glad.

  I Industrial Engineering and Management. 130 participants. Lecturer: Svante Gunnarsson.

  TB, KB Engineering Biology and Chemical Biology Programs. 45 participants. Lecturer: Thomas Schön.

  IT Information Technology. 20 participants. Lecturer: Martin Enqvist.

- *Control Theory* (Reglerteori). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Multivariable systems, Fundamental limitations in feedback control systems, LQG-control, Loop transfer recovery, Loop shaping methods, Nonlinear systems, Optimal control. 45 participants. Lecturer: Lennart Ljung.

- *Automatic Control M, advanced course* (Reglerteknik, fortsättningskurs M). For the Mechanical Engineering Program. Multivariable systems, Nonlinear systems. 30 participants. Lecturer: Svante Gunnarsson.

- *Digital Signal Processing* (Digital signalbehandling). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Spectral analysis, Filtering, Signal Modeling, Wiener and Kalman filtering, Adaptive filters. 90 participants. Lecturer: Thomas Schön.

- *Sensor Fusion* (Sensorfusion). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Estimation and detection theory, Sensor networks, Linear and non-linear filters, SLAM. 40 participants. Lecturer: Fredrik Gustafsson.

- *Optimal Control* (Optimal styrning). For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. The maximum principle, The Hamilton-Jacobi-Bellman equation, Numerical methods for solving optimal control. 30 participants. Lecturer: Anders Hansson.

- *Modelling and Simulation* (Modellbygge och simulering). For the Applied Physics and Electrical Engineering program. Physical system modelling, Bond graphs, Identification methods, Simulation. 60 participants. Lecturer: Torkel Glad.

- *Industrial Control* (Industriell reglerteknik). For the Applied Physics and Electrical Engineering, Computer Science and Engineering and Industrial Engineering and Management Programs. Numerical control, Binary control and PLCs, Process computers, Model predictive control, Monitoring and applications of digital process control. 60 participants. Lecturer: Martin Enqvist.

- *Control Project Laboratory* (Reglerteknisk projektkurs) For the Applied Physics and Electrical Engineering and Computer Science and Engineering Programs. Modelling and identification of laboratory processes, Controller design and implementation, Sensor fusion. 45 Participants. Lecturer: David Törnqvist.

- *Introduction to MATLAB* (Introduktionskurs i MATLAB). Available for several engineering programs. 300 participants. Lecturer: Johan Löfberg

- *Project Work* (Ingenjörsprojekt Y). Develop an understanding of what engineering is all about and how the work is performed. Administration, Planning, Communication, Documentation and presentation of project work. 12 participants. Lecturer: Svante Gunnarsson.

- *Perspectives to Computer Technology* (Perspektiv på datateknik). Project work with focus on computer technology. 6 participants. Lecturer: External.

B. Sc. (tekn.kand.)-program

- *Automatic Control.* Dynamical systems, The feedback principle, Frequency domain analysis and design of control systems, Robustness and sensitivity of control systems, Sampling, Implementation, Some examples of nonlinearities in control systems, Simulation of dynamic systems. 90 participants. Lecturer: Ragnar Wallin.

- *Automatic Control.* Sequential control and logic controllers, A typical industrial control system. 45 participants. Lecturer: Ragnar Wallin.

B.2 Graduate Courses

- *Dynamic Programming* Lecturer: Anders Hansson.

- *System Identification.* Literature: L. Ljung, System Identification: Theory for the User. Prentice Hall 1999, 2nd ed. Lecturer: Lennart Ljung.

- *Convex Optimization for Control.* Literature: Boyd, S. and L. Vandenberghe, Convex Optimization, Cambridge University Press, 2004. Lecturer: Anders Hansson.

- *Sensor Fusion.* Literature: F. Gustafsson, Statistical Sensor Fusion. Studentlitteratur, 2010. Lecturer: Fredrik Gustafsson.

- *Applied Control and Sensor Fusion.* Course coordinators: Martin Enqvist, David Törnqvist.
- *Linear systems.* Literature: Wilson J. Rugh, Linear System Theory, Prentice Hall, 1996. Lecturer: Torkel Glad.
- *Target tracking.* Literature: S. Blackman and R. Popoli, Design and Analysis of Modern Tracking Systems, Artech House, Norwood MA, 1999. Lecturer: Umut Orguner.

Appendix C

Seminars

- *Multi-User Transmit Beamforming using Convex Optimization.* **Eleftherios Karipidis**, Communication Systems, ISY, Linköping University. January 14, 2010.
- *Collaborating Swarms, Multi-network Topologies and Constrained Coalitional Games.* **John S. Baras**, University of Maryland College Park. January 20, 2010.
- *Finding Pedestrians in the Dark.* **Jacob Roll & Fredrik Tjärnström**, Autoliv, Linköping. January 21, 2010.
- *Dirichlet Process for Multi-target Tracking in Application to Dynamic Speech Spectrum Representation and Tracking Vocal Tract Resonance Frequencies.* **Emre Özkan**, Middle East Technical University, Ankara, Turkey. January 28, 2010.
- *Topics in Particle Filtering/Smoothing.* **Saikat Saha**, Automatic Control, ISY, Linköping University. February 4, 2010.
- *Smoothing in General Hidden Markov Models using Sequential Monte Carlo Methods.* **Jimmy Ohlsson**, Lund University. February 11, 2010.
- *Automatic Milking of Cows - with a Cool Robot!* **Ola Markusson**, DeLavall. February 18, 2010.
- *Modeling and Simulation in Practice.* **Jan Brugård**, Mathcore, Linköping. February 25, 2010.

- *A System Identification Challenge from Biology: To Combine Identifiability with Interpretability*. **Gunnar Cedersund**, IBK, Linköping University. March 4, 2010.

- *Challenges in Digital Signal Processing for Improved Performance of AD-conversion*. **Frida Eng**, SP Devices, Linköping. March 11, 2010.

- *Guidance of Sounding Rockets*. **Anders Helmersson**, Ruag, Linköping. March 18, 2010.

- *Control and Identification of Distributed Systems*. **Michel Verhaegen**, Delft University of Technology, Delft, The Netherlands. April 15, 2010.

- *Data Driven Fault Detection and Identification Connected to Subspace Identification*. **Jianfei Dong**, Delft University of Technology, Delft, The Netherlands. April 22, 2010.

- *Generalized Principal Component Analysis: An Introduction*. **Shankar Sastry**, UC Berkeley. April 27, 2010.

- *Docent Lecture: Nonlinear Filtering with Sensor Fusion Applications*. **Rickard Karlsson**, Nira Dynamics, Linköping. May 4, 2010.

- *Verification and Control of Hybrid Systems using Reachability Analysis*. **Claire Tomlin**, Stanford/UC Berkeley. May 5, 2010.

- *Past, Present and the Future of the Gripen Control System*. **Robert Hillgren**, Saab, Linköping. May 6, 2010.

- *The Dynamics of Confusion and Consensus in Cooperative Multi-agent Systems*. **Roy Smith**, University of California, Santa Barbara, USA. May 25, 2010.

- *Honorary Doctoral Lecture: Utmaningen att leverera mobila system till en global marknad*. **Marie Westrin**, Ericsson, Linköping. May 21, 2010.

- *Honorary Doctoral Lecture: Optimal Experiment Design for Open and Closed-loop Identification*. **Michel Gevers**, Université Catholique de Louvain, Belgium. May 21, 2010.

- *Optimal Experiment Design for Open and Closed-loop Identification, cont'.* **Michel Gevers**, Université Catholique de Louvain, Belgium. May 21, 2010.
- *Dirty Radio — a Smorgasbord with Modeling, Measurements, Pre- and Post-distortion.* **Peter Händel**, KTH, Stockholm. May 27, 2010.
- *Opportunistic Networks meet Infrastructure.* **George Theodorakopoulos**, EPFL, Lausanne, Switzerland. June 15, 2010.
- *My First Billion Control Loops.* **Bo Bernardsson**, Lund University. June 16, 2010.
- *Modeling and Optimization of a Hot Rolling Mill.* **Anders Daneryd**, ABB. August 26, 2010.
- *Development of new Array Signal Processing Techniques using Swarm Intelligence* . **Mehmet B. Guldogan**, Automatic Control, ISY, Linköping University. September 9, 2010.
- *Guaranteed Predictions in spite of Limited Knowledge and Uncertainties? — A Case Study for the NF-kB Signaling Pathway.* **Jan Hasenauer**, University of Stuttgart, Germany. September 20, 2010.
- *Stable Throughput, Rate Control, and Delay in Multi-access Channels.* **Anthony Ephremides**, University of Maryland. September 28, 2010.
- *Sniper Localization Based on Microphone Networks.* **David Lindgren**, FOI, Linköping. October 21, 2010.
- *Target Tracking Algorithms based on a New Generation of Set Theory.* **Lennart Svensson**, Chalmers university, Gothenburg. October 28, 2010.
- *A Particle-based Markov Chain Monte Carlo Sampler for State Space Models with Applications to DNA Copy Number Data.* **Susann Stjernqvist**, Lund university. November 1, 2010.
- *Optimized Behavioral Interventions: What Does Control Systems Engineering Have to Offer?* **Daniel E. Rivera**, Arizona state university. November 15, 2010.

- *Hierarchical Model Predictive Control for Smart Grid Consumer Control.* **Jakob Stoustrup**, Aalborg University, Denmark. November 17, 2010.

- *Robot Interaction Control Using Force and Vision.* **Bruno Siciliano**, Napoli university, Italy. December 3, 2010.

Appendix D

Travels and Conferences

Daniel Ankelhed participated in Reglermöte 2010, Lund, June 7–9.

Tohid Ardeshiri participated in a course on distributed optimization at the Royal Institute of Technology, Stockholm, February 8–12.

Daniel Axehill participated in the OPTEC Workshop on Large Scale Convex Quadratic Programming – Algorithms, Software, and Applications in Leuven, Belgium, November 25–26. He also participated in the 49th IEEE Conference on Decision and Control, in Atlanta, USA, December 13–18.

Patrik Axelsson participated in Reglermöte 2010, Lund, June 7–9.

Jonas Callmer participated in Reglermöte 2010, Lund, June 7–9 and the International Conference on Information Fusion, Edinburgh, UK, July 26–29. He also participated in the Workshop on Indoor Navigation at the Royal Institute of Technology in Stockholm, Sweden on August 19.

André Carvalho Bittencourt participated in Reglermöte 2010 in Lund, June 7–9. He attended the IV International Summer School on Fault Diagnosis of Complex Systems in Girona, Spain, July 5–9, and the IEEE/RSJ International Conference on Intelligent Robots and Systems in Taipei, Taiwan, October 18–22.

Tianshi Chen participated in the 19th ERNSI Workshop on System Identification, Cambridge, UK, September 26–29, and the 49th IEEE Conference on Decision and Control, in Atlanta, USA, December 13–18.

Martin Enqvist participated in the 5th International workshop on Analysis of Dynamic Measurements, SP Technical Research Institute of Sweden, Borås, Sweden, June 1, Reglermöte 2010, Lund, June 7–9, and the 19th ERNSI Workshop on System Identification, Cambridge, UK, September 26–29.

Rikard Falkeborn participated in the 2nd Workshop on Clearance of Flight Control Laws, Stockholm, January 28–29, a course on distributed optimization at the Royal Institute of Technology, Stockholm, February 8–12 and Relglermöte 2010, Lund, June 7–9.

Torkel Glad participated in Reglermöte 2010 in Lund, June 7–9.

Karl Granström participated in Reglermöte 2010, Lund, June 7–9, International Conference on Information Fusion, Edinburgh, UK, July 26–29 and IEEE/RSJ International Conference on Intelligent Robots and Systems, 2010, Taipei, Taiwan, October 18–22.

Svante Gunnarsson participated in Reglermöte 2010, Lund, June 7–9, the 6th International CDIO Conference, Montreal, Canada, June 16–17, International Crossroads at Telecom SudParis, Evry, France, May 6–7, and the CDIO Nordic Regional Meeting, Umeå, October 5–6. In January he participated in a delegation from Linköping University visiting a number of universities in Japan, including Tokyo University, Kyoto University, Osaka University, and Kyushu University.

Fredrik Gustafsson participated in Ph. D. committees in Zürich, Trondheim, and Brussels. He participated in Reglermöte 2010, Lund, June 7–9 and the International Conference on Information Fusion, Edinburgh, UK, July 26–29.

Anders Hansson participated in the 2nd Workshop on Clearance of Flight Control Laws, Stockholm, January 28–29. He participated in the LCCC workshop in Lund, May 18–28, and in Reglermöte 2010, Lund, June 7–9. He attended the EUCA council meeting in Budapest, August 30–31. He participated the IEEE Multi-conference on systems and control in Yokohama, September 7–11. He visited Tokyo Institute of Technology on September 9.

Ylva Jung participated in Reglermöte 2010, Lund, June 7–9 and the 19th ERNSI Workshop on System Identification held at Cambridge, UK, September 26–29.

Sina Khoshfetrat Pakazad participated in Reglermöte 2010, Lund, June 7–9.

Roger Larsson participated in the 19th ERNSI Workshop on System Identification, Cambridge, UK, September 26–29 and Flygteknik 2010 in Stockholm, Sweden, October 18–19.

Fredrik Lindsten participated in the 2010 IEEE International Conference on Robotics and Automation, Anchorage, USA, May 3–8 and in Reglermöte 2010, Lund, June 7–9. He visited Lund University as a guest researcher for two weeks during September. He also participated in the 19th ERNSI Workshop on System Identification held at Cambridge, UK, September 26–29 and in the 49th IEEE Conference on Decision and Control, in Atlanta, USA, December 13–18.

Lennart Ljung participated in the micro-workshop on System Identification at VUB in Brussels, Feb 24–25, and was a member of the committee that evaluated NTU in Singapore, March 1–7. He participated in the LCCC workshop in Lund, April 21–23, and in Reglermöte 2010, Lund June 7–9. He visited the Academy of Mathematics and Systems Science in Beijing on July 28, and took part in the 29th Chinese Control Conference in Beijing, July 29–31. He spent part of the fall at Lund Institute of Technology, and participated in the workshop celebrating Michel Gevers's 65th birthday in Louvain-la-Neuve, October 27–29. December 6–10 he took part in the IEEM conference in Macao, and December 13–18 he participated in the 49th IEEE Conference on Decision and Control, in Atlanta, USA.

Christian Lundquist participated in Reglermöte 2010, Lund, June 7–9, the International Conference on Information Fusion, Edinburgh, UK, July 26–29 and European Signal Processing Conference, 2010, Aalborg, Denmark, August 23–27.

Johan Löfberg participated in Reglermöte 2010, Lund, June 7–9 and the 2010 IEEE Multi-Conference on Systems and Control, Yokohama, Japan, September 8–10. He visited the Automatic Control Laboratory at ETH Zürich, Switzerland, March 15–20.

Mikael Norrlöf participated in Reglermöte 2010, Lund, June 8, and in the ELLIIT workshop, Linköping, November 11.

Henrik Ohlsson participated in the LCCC workshop in Lund, April 21–23 and in Reglermöte 2010, Lund, June 7–9. He also participated in the European Research Network on System Identification workshop held at Cambridge, UK, 26–29 of September and in the 49th IEEE Conference on Decision and Control, in Atlanta, USA, December 13–18.

Umut Orguner participated in the kick-off meeting of the McImpulse project (EU FP7 Marie Curie Initial Training Network) at Thales Nederland B.V. in Hengelo, The Netherlands, during January 18–20. He also attended the 13th International Conference on Information Fusion, Edinburgh, UK, July 26–29.

Daniel Petersson participated in the 2nd Workshop on Clearance of Flight Control Laws, Stockholm, January 28–29, Reglermöte 2010, Lund, June 7–9 and the 2010 IEEE Multi-Conference on Systems and Control, Yokohama, Japan, September 8–10.

Peter Rosander participated in the SSF Conference — New tools for improved profitability in the Process industry, Stockholm, April 21, and in Reglermöte 2010, Lund, June 7–9.

Saikat Saha participated in Reglermöte 2010, Lund, June 7–9, and the International Conference on Information Fusion, Edinburgh, UK, July 26–29.

Thomas Schön visited Thales Nederland B.V. in Hengelo, The Netherlands, during January 21–22. He participated in the kick-off meeting for the ELLIIT project on navigation held at Lund University on February 4. He participated in the Workshop on Swedish robotics research: Trends, applications and challenges, Royal Institute of Technology in Stockholm, Sweden on April 19. He visited The Department of Signals and Systems at Chalmers University of Technology in Göteborg, Sweden on April 23 and May 19. He visited the Swedish Defence Research

Agency in Linköping, Sweden on June 3. He participated in Reglermöte 2010, Lund, June 7–9. He also participated in the Workshop on Indoor Navigation at the Royal Institute of Technology in Stockholm, Sweden on August 19. During the time August 24 – September 30 he visited the School of Electrical Engineering and Computer Science at the University of Newcastle, Newcastle, Australia. He visited the Pacific Northwest National Laboratory in Richland, USA on November 15, and on November 17 he visited Rutgers University, New Brunswick, USA. He also visited the Science and Technology Directorate at the U.S. Department of Homeland Security, Washington DC, USA on November 18–19. He participated in the 49th IEEE Conference on Decision and Control in Atlanta, USA, December 15–17.

Zoran Sjanic participated in Reglermöte 2010, Lund, June 7–9, 13th International Conference on Information Fusion, Edinburgh, UK, July 26–29 and Flygteknik 2010, Stockholm, October 18–19.

Per Skoglar participated in the IEEE Aerospace Conference, Big Sky, March 6–13, and in Reglermöte 2010, Lund, June 7–9, and in the TAMSEC symposium, Linköping, October 27–28. He also visited C3UV at the University of California, Berkeley, March 15–19.

Martin Skoglund participated in Reglermöte 2010, Lund, June 7–9.

David Törnqvist participated in the kick-off meeting for the ELLIIT project on navigation held at Lund University on February 4. He participated in the IEEE Aerospace Conference, Big Sky, March 6–13, and in Reglermöte 2010, Lund, June 7–9, and in the TAMSEC symposium, Linköping, October 27–28. He also visited C3UV at the University of California, Berkeley, March 15–19. He also participated in the Workshop on Indoor Navigation at the Royal Institute of Technology in Stockholm, Sweden on August 19. He participated in a workshop organized by the Swedish National Space Technology Research Programme at the Royal Institute of Technology, Stockholm, Sweden, November 1.

Niklas Wahlström participated in the International Conference on Information Fusion, Edinburgh, UK, July 26–29 and visited Luleå University of Technology, Luleå, on October 18–20.

Johanna Wallén participated in Reglermöte 2010, Lund, June 7–9. She regularly visited the Department of Automatic Control in Lund during the spring 2010. She also attended the LINK-SIC workshop in Linköping, November 8, and the ELLIIT workshop in Linköping, November 11–12.

Emre Özkan participated in the kick-off meeting of the McImpulse project (EU FP7 Marie Curie Initial Training Network) at Thales Nederland B.V. in Hengelo, The Netherlands, during January 18–20. He also attended the 13th International Conference on Information Fusion, Edinburgh, UK, July 26–29.

Appendix E

Lectures by the Staff

- Daniel Ankelhed: *A Primal-Dual Method for Low Order H-infinity Controller Synthesis*, Reglermöte 2010, Lund, Sweden, June 9.

- Daniel Axehill: *A Dual Active Set-Like Quadratic Programming Algorithm Tailored for Model Predictive Control*, OPTEC Workshop on Large Scale Convex Quadratic Programming – Algorithms, Software, and Applications, Leuven, Belgium, November 26.

- Jonas Callmer: *Realtidspositionering av rökdykare*, Rökdykarforum, Lambohovs Brandstation, Linköping, March 12.

- Jonas Callmer: *Probabilistic Stand Still Detection using Foot Mounted IMU*, Linköping – Freiburg Workshop on Learning World Models, Linköping, June 21.

- Jonas Callmer: *Probabilistic Stand Still Detection using Foot Mounted IMU*, International Conference on Information Fusion, Edinburgh, UK, July 27.

- Jonas Callmer: *Foot Mounted INS Activities at LiU*, Workshop on Indoor Navigation at Linköping University, August 27.

- Martin Enqvist: *Estimating Dynamic Models from Measurements Using System Identification Methods*, Keynote lecture at the 5th International workshop on Analysis of Dynamic Measurements, SP Technical Research Institute of Sweden, Borås, Sweden, June 1.

- Rikard Falkeborn: *Structure Exploitation in Semidefinite Programming for Control*, Techn. Lic. presentation at Linköping University, Sweden, February 17.

- Karl Granström: *A Gaussian Mixture PHD Filter for Extended Target Tracking*, International Conference on Information Fusion, Edinburgh, UK, July 27.

- Karl Granström: *Learning to Close the Loop from 3D Point Clouds*, IEEE/RSJ International Conference on Robots and Intelligent Systems, Taipei, Taiwan, October 20.

- Svante Gunnarsson: *Possibilities and Reasons for International Students to Study at Linköping University.* International Crossroads at Telecom SudParis, Evry, France, May 6.

- Svante Gunnarsson: *IUAE Matrices Revisited — Current Activities at Linköping University*, CDIO Nordic Regional Meeting, Umeå, October 6.

- Svante Gunnarsson: *Using CDIO Standards 2.0 for Program Evaluation — Some Experinces*, CDIO Nordic Regional Meeting, Umeå, October 6.

- Fredrik Gustafsson: *Fusion in Sensor Networks*, Twente university, The Netherlands, January 19.

- Fredrik Gustafsson: *Fusion in Sensor Networks*, ETH, Switzerland, May 6.

- Fredrik Gustafsson: *Sensornätverk för säkerhets skull (Sensor Networks for the Sake of Security)*, Plenary presentation, Reglermöte 2010, Lund, June 8.

- Fredrik Gustafsson: *Sensor Networks for the Sake of Security*, Cambridge University, UK, July 22.

- Anders Hansson: *Towards Parallel Implementation of Hybrid MPC — A Survey and Directions for Future Research*, Workshop on Distributed Model Predictive Control and Supply Chains, Lund, May 20.

- Anders Hansson: *A Structure Exploiting Preprocessor for Semidefinite Programs derived from the Kalman-Yakubovich-Popov Lemma*, Tokyo Institute of Technology, Japan, September 9.

- Fredrik Lindsten: *Geo-referencing for UAV Navigation using Environmental Classification*, IEEE International Conference on Robotics and Automation, Anchorage, USA, May 4.

- Fredrik Lindsten: *Geo-referencing for UAV Navigation using Environmental Classification*, Linköping – Freiburg Workshop on Learning World Models, Linköping, June 21.

- Fredrik Lindsten: *Identification of Mixed Linear/Nonlinear State-Space Models*, 49th IEEE Conference on Decision and Control, Atlanta, USA, December 17.

- Lennart Ljung: *Semi-Supervised Regression and System Identification*, the LCCC Symposium, Lund, April 22.

- Lennart Ljung: *Sum-of-Norm Regularization in Estimation Problems — Preliminary Results*, Academy of Mathematics and Systems Science, Beijing, China, July 28.

- Lennart Ljung: *Approaches to Identification of Nonlinear Systems*. Plenary presentation at 29th Chinese Control Conference, Beijing, China, July 29.

- Lennart Ljung: *Excellence Centers — with Relevance to Link-Lab and SAAB*, Link-Lab workshop, Norrköping, September 21.

- Lennart Ljung: *MOVIII — Some General Reflections*, Final MOVIII workshop, Norrköping Visualization Center, Norrköping, October 14.

- Lennart Ljung: *Sum-of-Norm Regularization in Estimation Problems*, the Michel Gevers Celebration Conference, Lovain-la-Neuve, Belgium, October 28.

- Lennart Ljung: *The Goal of ELLIIT*, Address at the first ELLIIT workshop, Linköping, November 11.

- Lennart Ljung: *System Identification: The Path from Data to Model*, Plenary presentation, IEEE International Conference on Industrial Engineering and Engineering Management, Macao, China, December 8.

- Christian Lundquist: *Road Mapping using Radar Measurements with a Probability Hypothesis Density Filter*, Linköping – Freiburg Workshop on Learning World Models, Linköping, June 21.

- Christian Lundquist: *Estimating Polynomial Structures from Radar Data*, International Conference on Information Fusion, Edinburgh, UK, July 27.

- Christian Lundquist: *A Gaussian Mixture PHD Filter for Extended Target Tracking*, European Signal Processing Conference, Aalborg, Denmark, August 24.

- Johan Löfberg: *Automatic Robust Convex Programming*, ETH Zürich, Switzerland, March 15.

- Johan Löfberg: *Low Rank Exploitation in Semidefinite Programming for Control*, 2010 IEEE Multi-Conference on Systems and Control, Yokohama, Japan, September 8.

- Mikael Norrlöf: *Process Learning — Project Presentation*, ELLIIT Workshop, Linköping University, November 11.

- Henrik Ohlsson: *Trajectory Generation Using Sum-Of-Norms Regularization*, 49th IEEE Conference on Decision and Control, Atlanta, USA, December 15.

- Henrik Ohlsson: *State Smoothing by Sum-of-Norms Regularization*, 49th IEEE Conference on Decision and Control, Atlanta, USA, December 16.

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- Daniel Petersson: *Identification of State-space LPV-models using H_2-Minimization*, 2nd Workshop on Clearance of Flight Control Laws, Stockholm, January 28.

- Daniel Petersson: *Robust Generation of LPV State-Space Models Using a Regularized H_2-Cost*, 2010 IEEE Multi-Conference on Systems and Control, Yokohama, Japan, September 8.
- Daniel Petersson: *Nonlinear Optimization Approaches to H_2-Norm Based LPV Modelling and Control*, Techn. Lic. presentation at Linköping University, Sweden, November 24.
- Saikat Saha: *Marginalized Particle Filters for Bayesian Estimation of Gaussian Noise Parameters*, International Conference on Information Fusion, Edinburgh, UK, July 28.
- Thomas Schön: *Some Ongoing Research — Application Oriented*, Workshop on Swedish robotics research: Trends, applications and challenges, Royal Institute of Technology, Stockholm, Sweden, April 19.
- Thomas Schön: *System Identification of Nonlinear State-space Models*, Department of Signals and Systems, Chalmers University of Technology, Göteborg, Sweden, May 19.
- Thomas Schön: *Sensor Data Fusion*, Swedish Defence Research Agency, Linköping, Sweden, June 3.
- Thomas Schön: *The Use of Camera Information in Solving Sensor Fusion Problems*, Workshop on Indoor Navigation, Royal Institute of Technology, Stockholm, Sweden, August 19.
- Thomas Schön: *Sensor Fusion Using Inertial and UWB Sensors*, Workshop on Indoor Navigation, Royal Institute of Technology, Stockholm, Sweden, August 19.
- Thomas Schön: *Sensor Fusion Using Inertial Sensors, Cameras and Ultra-Wideband*, The School of Electrical Engineering and Computer Science, University of Newcastle, Newcastle, Australia, September 29.
- Thomas Schön: *Bilar utan förare i trafiken — livsfarligt eller säkert?*, Teknikfestival, Norrköping, December 1.
- Thomas Schön: *Estimating State-Space Models in Innovations Form using the Expectation Maximisation Algorithm*, 49th IEEE Conference on Decision and Control, Atlanta, USA, December 17.

- Thomas Schön: *Estimation of General Nonlinear State-Space Models*, 49th IEEE Conference on Decision and Control, Atlanta, USA, December 17.
- Zoran Sjanic: *Solving the SLAM Problem for Unmanned Aerial Vehicles Using Smoothed Estimates*, Linköping – Freiburg Workshop on Learning World Models, Linköping, June 21.
- Zoran Sjanic: *Simultaneous Navigation and SAR Auto-focusing*, International Conference on Information Fusion, Edinburgh, UK, July 26.
- Per Skoglar: *Autonoma funktioner för stöd till UAV-operatörer*, Saab , Linköping, Sweden, February 26.
- Per Skoglar: *Combined Point-Mass and Particle Filter for Target Tracking*, IEEE Aerospace Conference, Big Sky, USA, March 10.
- Per Skoglar: *Particle Filtering with Propagation Delayed Measurements*, IEEE Aerospace Conference, Big Sky, USA, March 10.
- Johanna Wallén: *A Framework for Analysis of Observer-based ILC*, Reglermöte 2010, Lund, June 8.
- Niklas Wahlström: *Magnetometers for Tracking Metallic Targets*, International Conference on Information Fusion, Edinburgh, UK, July 30.
- Niklas Wahlström: *Magnetometers for Tracking Metallic Targets*, Luleå University of Technology, Luleå, October 20.

Appendix F

Publications

Phd Theses

[1] S. Moberg. *Modeling and Control of Flexible Manipulators.* Linköping studies in science and technology. Dissertations. No. 1349, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec. 2010. URL http://www.control.isy.liu.se/publications/doc?id=2342.

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Appendix G

Technical Reports

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Appendix H

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