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Abstract

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Final Report STU 85-3225

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Abstract. This is a final report for the STU project 85-3225 carried out in the period July 1985 to June 1988. The research covers multivariable adaptive control, adaptive stabilization, dual control, robustness issues, automatic tuning and adaptive friction compensation.

1. Introduction

Adaptive control has been a research theme at the Department of Automatic Control at the Lund Institute of Technology since the department was started in 1965. The research has been quite successful. Many papers have been written and our group is now internationally regarded as one of the leaders in the field, which can be judged by awards and invitations. Our research in adaptive control has also had industrial impact both in Sweden and abroad. There are currently five Swedish companies: ABB, First Control, Gambro, SattControl, and Kockum Sonics, that are marketing adaptive systems. Former students from our department are major factors in this development.

The purpose of this particular research project has been to deepen our understanding of adaptive control systems. Three problem areas have been investigated: analysis of robustness of adaptive systems, analysis of

The possibilities of having a close interaction with visiting researchers have proven extremely useful. It has allowed us to bring in many researchers with specialized expertise that complement our own. Eleven researchers have been visiting us for longer periods. We also reciprocated by lecturing on our results at many institutions.

Altogether the work has resulted in 3 books, one PhD thesis, 2 Lic Tech theses, 54 papers, 9 master theses, 32 reports, and interesting collaboration with industry. Research work initiated in the project by a visiting researcher, Carlos Canudas de Wit, has also resulted in a PhD thesis in Grenoble, France. The key staff members who contributed to the project were Rolf Johansson, Bengt Mårtensson, Björn Wittenmark, and K. J. Åström.

A list of the visitors who contributed is given in Appendix A. The books written are given in Appendix B, the papers in Appendix C, reports in Appendix D, and patents in Appendix E. A list of the lectures given by our staff at other institutions is given in Appendix F.

2. Multivariable Adaptive Control

Most control systems for industrial processes are designed from a single-input-single-output point of view. This is appropriate only if the coupling between the different loops is weak. There are, however, many multivariable processes where there is strong coupling between the loops. It is then important to consider this coupling when designing the control system. Further it may be desirable to control the different loops individually. To do this a decoupler must be designed to separate the different control loops. There is a large amount of theory for design of multivariable feedback systems and decouplers. This is based on the assumption that mathematical models of the systems are known. The models must also be known quite accurately since the decoupler critically depends on the internal structure and parameters of the system. A number of multivariable adaptive problems have been explored by Johansson. Algorithms and analysis for decoupling with adaptive control are given by Johansson (1987) and by Wittenmark et al. (1988).

An industrial robot is a typical example of a multivariable system. It has many measured and manipulated signals. Adaptive control of an

by Bernhardsson (1989). Although these are all special cases the insight gained will contribute to our understanding of adaptive systems.

5. Robustness

Convergence and stability problems for some classes of adaptive controllers were solved in the late 1970' and early 1980'. The assumptions made were highly idealistic. Typically it was assumed that the order of the system and the time delay was known. Lately it has been discovered that these assumptions are both critical and highly unrealistic. The empirical knowledge obtained from implementation of adaptive regulators has also indicated that the robustness problem is very important in practice. Similar problems also appear in adaptive signal processing. Several tricks have been used practically to solve the robustness problem. They include introduction of various filters and nonlinearities, which are suggested partly based on experience and partly based on analysis.

The consequences of using adaptive control laws based on simplified process models and applying them to complex systems have been investigated. The problem is difficult to tackle, because it leads to complicated nonlinear differential or difference equations. It has been found that averaging methods can give very useful insight into these problems. This has for example given a very interesting reevaluation of the advantages and disadvantages of some classical adaptive control schemes. The key results are summarized in the book Åström and Wittenmark (1989).

The robustness problem is closely related to implementation issues. Several ideas to improve robustness originated in connection with implementation and the analysis tools give a possibility to investigate their effects in simple cases. Implementation issues have therefore also been investigated in a number of papers by Wittenmark and Åström.

The work on robustness has also given insights to start a new research direction. Design methods used in current adaptive systems are fairly simple like pole placement and LQG. Current adaptive systems are also based on the assumption of certainty equivalence, i.e., the uncertainty in the model is not considered when making the control design. There are, however, so called robust design methods which explicitly take uncertainties into account. The design methods are not easy to automate, because they

tems with periodic excitation. This idea has also been patented.

The work on automatic tuning of PID regulators has also led us to reconsider the classical problem of finding simple methods for determining if PID control can be used and how the regulator parameters can be chosen. This work has also given rewarding results.

As a result of our work on automatic tuning of PID controllers we were invited by ISA (Instrument Society of America) to summarize our results in a monograph.

A large number of reports and papers have also been written in the area of automatic tuning, see papers by Åström and Hägglund.

Although significant progress has been made there is still a fundamental theoretical mathematical problem that we have not yet been able to solve namely: Determine the class of all linear systems which will have a stable limit cycle under relay feedback. Determine stability conditions for the limit cycle. Some progress has been made on this problem although we do not yet have a complete solution.

The auto-tuning algorithms are of interest in a more general framework, because they can be used to initialize other adaptive algorithms like the model reference algorithm or the self-tuning regulator which have the character of local gradient methods. A particularly interesting feature of the auto-tuners is that they will automatically generate an input signal.

7. Adaptive Friction Compensation

Most work on adaptive control so far has been based on the assumption that nothing is known about the process that we are controlling. A general linear model is then estimated recursively and the control law is computed from the estimated parameters. In practice the system is often partially known and the system can be nonlinear. It is therefore highly desirable to have results on adaptive control of partially known nonlinear systems. Since this is in general a very difficult problem, it seems worth while to start by analyzing some examples. By coincidence we were faced with a specific problem in our laboratory. This problem is adaptive friction compensation in motor drives of the type that is found in industrial robots. Research into that problem has given interesting and useful results. The work was carried out together with two visiting researchers Konrad Braun from ETH

A. Visiting Scientists

Mukul Agarwal,
Department of Chemical Engineering, University of California,
Santa Barbara, California, USA
(24 June – 20 Sept, 1985).

Professor Brian Anderson,
The Australian National University,
Canberra, Australia
(1–6 sept, 1986)

Professor Chris Byrnes,
Arizona State University, Dept of Mathematics,
Tempe, Arizona, USA
(1–8 April, 1986)

Carlos Canudas de Wit,
Laboratoire d'Automatique de Grenoble, France
(14 Jan – 29 Oct, 1985).

Professor Guy Dumont,
Pulp and Paper Research Institute of Canada,
The University of British Columbia, Vancouver, Canada
(14 May – 4 July, 1986).

Dr. Andras Edelmayer,
Hungarian Academy of Science,
Computer and Automation Institute,
Budapest, Hungary
(16–27 Nov, 1987)

Professor Robin Evans,
University of Newcastle, Dept of Electrical and Computer Eng.,
New South Wales, Australia
(7–9 October, 1987)

Professor Patrick Parks,
The Royal Military College of Science,
Dept of Mathematics & Ballistics,
Shrivenham, Swindon, UK
(3 May, 1988)

Jan Willem Poldermann,
Centrum voor Wiskunde en Informatica (CWI),
Amsterdam, The Netherlands
(8–9 September, 1986)

James H. Taylor,
General Electric Co., Schenectady, NY, USA
(16 – 21 Oct, 1985).

Professor J. Willems,
University of Groningen, Mathematical Institute,
Groningen, The Netherlands
(1–5 April, 1986)

C. Published Papers and Conference Contributions

Åström, K. J. (1985): "Towards intelligent control," *IEE International Conference on Control '85*, Venue, UK.

Åström, K. J. (1986a): "Adaptation, auto-tuning and smart controls," in M. Moran and T. S. McAvoy (Eds.): *Chemical Process Control—CPC III*, Proc. 3rd International Conference on Chemical Process Control, Asilomar, California, CACHE, Elsevier.

Åström, K. J. (1986b): "Adaptive friction compensation for robot manipulators," *IEEE International Conference on Robotics and Automation*, San Francisco, California, USA.

Åström, K. J. (1986c): "Towards intelligent control," *Proc. Control Systems '86*, Stockholm, Sweden, p. 198.

Åström, K. J. (1986d): "Expert control," Introduction to a round table discussion on expert systems in Automatic Control, *IFAC Symposium on Large Scale Systems*, Zürich, Switzerland.

Åström, K. J. (1986e): "A perspective on control engineering," Keynote talk, *IEEE Workshop on the Challenge to Control*, Santa Clara, California, USA.

Åström, K. J. (1987a): "Adaptive control: Fundamental problems," in M. G. Singh (Ed.): *Systems and Control Encyclopedia*, Vol. 1, Pergamon Press, pp. 45–47.

Åström, K. J. (1987b): "Applications of adaptive control to paper making," in M. G. Singh (Ed.): *Systems and Control Encyclopedia*, Vol. 1, Pergamon Press.

Åström, K. J. (1987c): "Adaptive feedback control," Invited paper, *Proceedings of the IEEE*, **75**, February, 185–217.

Åström, K. J. (1987d): "Stochastic control theory," Invited plenary paper, *First International Conference on Industrial and Applied Mathematics*, Paris, France.

Canudas, C., K. J. Åström, and K. Braun (1987): "Adaptive friction compensation in DC-motor drives," *IEEE J. Robotics and Automation*, **RA-3**, 681–685.

Dumont, G. A., and K. J. Åström (1987): "On chip refiner control," *Proc. 1987 American Control Conference (ACC)*, Minneapolis, Minnesota, USA.

Grimble, M. J., and K. J. Åström (1987): "Frequency-domain properties of Kalman filters," *Int. J. Control*, **45**, 907–925.

Holmberg, U. (1986): "Adaptive dissolved oxygen control and on-line estimation of oxygen transfer and respiration rates," *AIChE Annual Meeting*, Miami Beach, Florida, USA.

Hägglund, T. (1985): "Recursive estimation of slowly time-varying parameters," *Preprints 7th IFAC/IFORS Symposium on Identification and System Parameter Estimation*, York, UK.

Johansson, R. (1985a): "Estimation and direct adaptive control of delay-differential systems," *Preprints 7th IFAC/IFORS Symposium on Identification and System Parameter Estimation*, York, UK.

Johansson, R. (1985b): "Direct adaptive control—Global Lyapunov stability and exponential convergence," GRECO report, Laboratoire d'Automatique de Grenoble, France.

Johansson, R. (1986a): "Recursive identification of continuous-time dynamic systems," GRECO Report, Laboratoire d'Automatique de Grenoble, France.

Johansson, R. (1986b): "Stability of direct adaptive control with RLS identification," in C. I. Byrnes and A. Lindquist (Eds.): *Modelling, identification, and robust control*, North Holland, Amsterdam, The Netherlands.

Johansson, R. (1986c): "Direct adaptive control—Global Lyapunov stability and exponential convergence," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece.

Johansson, R. (1986d): "Identification of continuous-time dynamic systems," *Proc. 25th IEEE Conf. on Decision and Control*, Athens, Greece.

Wallenborg, A., and K. J. Åström (1988): "Limit cycle oscillations in high performance robot drives," *Preprints Control '88*, University of Oxford, UK.

Wittenmark, B. (1986a): "A property of the extra zeros due to sampling," Report EE8635, October 1986, Department of Electrical and Computer Engineering, University of Newcastle, Australia.

Wittenmark, B. (1986b): "On the role of filters in adaptive control," Report EE8662, December 1986, Department of Electrical and Computer Engineering, University of Newcastle, Australia.

Wittenmark, B. (1987a): "Adaptive stability augmentation or how to use a priori knowledge," Report EE8713, March 1987, Department of Electrical and Computer Engineering, University of Newcastle, Australia.

Wittenmark, B. (1987b): "Self-tuning control: General aspects," in M. G. Singh (Ed.): *Systems and Control Encyclopedia*, Pergamon Press, pp. 4190–4193.

Wittenmark, B. (1987c): "Self-tuning proportional-integral-derivative controllers: Pole assignment approach," in M. G. Singh (Ed.): *Systems and Control Encyclopedia*, Pergamon Press, pp. 4211–4214.

Wittenmark, B. (1988a): "Implementation issues in adaptive control," Plenary lecture, *Preprints Workshop on Adaptive Control Strategies for Industrial Use*, Banff, Canada.

Wittenmark, B. (1988b): "Adaptive stability augmentation," *Preprints 8th IFAC Symposium on Identification and System Parameter Estimation*, Beijing, P. R. China.

Wittenmark, B. (1988c): "Implementation and application of adaptive control," Plenary lecture, *Preprints AdChem '88*, Lyngby, Denmark.

Wittenmark, B. and C. Elevitch (1985): "An adaptive control algorithm with dual features," *Preprints 7th IFAC/IFORS Symposium on Identification and System Parameter Estimation*, York, UK.

Wittenmark, B., and R. J. Evans (1988): "An adaptive pole placement controller based on pole-zero parameterization," *Preprints 8th IFAC Symposium on Identification and System Parameter Estimation*, Beijing, P. R. China.

D. Reports

Dissertations

Mårtensson, B. (1986): "Adaptive stabilization," PhD dissertation CODEN: LUTFD2/TFRT-1027, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Lic Tech Theses

Rundqwist, L. (1986): "Self-tuning control of the dissolved oxygen concentration in an activated sludge system," Lic Tech thesis CODEN: LUTFD2/TFRT-3180, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Holmberg, U. (1987): "Adaptive dissolved oxygen control and on-line estimation of oxygen transfer and respiration rates," Lic Tech thesis CODEN: LUTFD2/TFRT-3189, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Master Theses

Bernhardsson, B. (1986): "Implementation of fast recursive parameter estimation algorithms on the signal processor TMS 320," Master thesis CODEN: LUTFD2/TFRT-5351, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Fredenholm, J. (1987): "Primitiva adaptiva robotprogram," (Primitive adaptive robot programs), Master thesis CODEN: LUTFD2/TFRT-5368, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Jönsson, M. (1985): "Simulering av en hybrid självinställande regulator," (Simulation of a hybrid self-tuning controller), Master thesis CODEN: LUTFD2/TFRT-5334, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Jönsson, J. (1986): "Identifiering och reglering av förbränningen i en fluidiserande bädd," (Identification and control of the combustion in a fluidized bed), Master thesis CODEN: LUTFD2/TFRT-5352,

Åström, K. J. (1985): "Auto-tuning, adaptation and expert control," Internal report CODEN: LUTFD2/TFRT-7298, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström, K. J. (1986): "Adaptiv reglering," (Adaptive control), Final report CODEN: LUTFD2/TFRT-3185, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström, K. J. (1987): "Adaptation, auto-tuning and smart controls," Internal report CODEN: LUTFD2/TFRT-7340, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström, K. J. (1987): "Adaptive control—A way to deal with uncertainty," Internal report CODEN: LUTFD2/TFRT-7345, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström, K. J. (1988): "Dominant pole placement design of PI regulators," Internal report CODEN: LUTFD2/TFRT-7381, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström, K. J., L. Neumann, and P.-O. Gutman (1987): "A comparison between robust and adaptive control of uncertain systems," Internal report CODEN: LUTFD2/TFRT-7350, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Åström, K. J., L. Neumann, and P. O. Gutman (1987): "A comparison of robust and adaptive control," Internal report CODEN: LUTFD2/TFRT-7368, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Braun, K. (1985): "Implementation of an adaptive friction compensation," Internal report CODEN: LUTFD2/TFRT-7304, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Byrnes, C. I., U. Helmke, and A. S. Morse (1986): "Necessary conditions in adaptive control," Internal report CODEN: LUTFD2/TFRT-7319, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Canudas, C. (1985): "Adaptive friction compensation in DC motors," Internal report CODEN: LUTFD2/TFRT-7285, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Lundh, M. (1986): "Adaptive friction and load compensation based on shaft angle measurement in DC-motor servos," Internal report CODEN: LUTFD2/TFRT-7331, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Mårtensson, B. (1986): "CODEGEN—Automatic Simnon code generator for multivariable linear systems," Internal report CODEN: LUTFD2/TFRT-7323, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Mårtensson, B. (1986): "Adaptive stabilization of multivariable linear systems," Internal report CODEN: LUTFD2/TFRT-7324, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Mårtensson, B. (1986): "Adaptive stabilization without high-gain," Internal report CODEN: LUTFD2/TFRT-7326, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Mårtensson, B. (1986): "Dynamic high-gain stabilization of multivariable linear systems, with application to adaptive control," Internal report CODEN: LUTFD2/TFRT-7337, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Rohrs, C. E., G. Stein, and K. J. Åström (1985): "Uncertainty in sampled systems," Internal report CODEN: LUTFD2/TFRT-7296, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Rohrs, C. E., G. Stein, and K. J. Åström (1985): "A practical robustness theorem for adaptive control," Internal report CODEN: LUTFD2/TFRT-7297, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

Rundqwist, L. (1985): "Integral action and mode transitions in self-tuning process control," Internal report CODEN: LUTFD2/TFRT-7305, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

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E. Patents

Hägglund, T., and K. J. Åström (1985): *Method and an Apparatus in Tuning a PID-regulator*, U.S. Patent Number 4549123.

Åström, K. J., and T. Hägglund (1988): *Method and an Apparatus for Automatically Tuning a Process Regulator*, U.S. Patent Number 4758943.

Nov 20, 1985. Karl Johan Åström: "Why control is fun!," Acceptance speech for the Rufus Oldenburger medal, ASME Winter meeting, Miami, Florida, USA.

Nov 21, 1985. Rolf Johansson: "Multivariable adaptive control," Laboratoire de Statistique Appliquée, Université Paris XI, Orsay, France.

Nov 27, 1985. Björn Wittenmark: "Adaptiv reglering," (Adaptive control), Course for STF (Svenska Teknologföreningen), Kungälv, Sweden.

Dec 2, 1985. Björn Wittenmark: "Self-tuning regulators," IMSOR, Denmark Institute of Technology, Lyngby, Denmark.

Dec 11, 1985. Karl Johan Åström and Karl-Erik Årzén: "Intelligent controllers," Meeting of the AI interest group at Lund University, Lund, Sweden.

Jan 8, 1986. Rolf Johansson: "Signal processing aspects of continuous time system identification," CNRS GRECO, Laboratoire d'Automatique de Grenoble, Grenoble, France.

Jan 15, 1986. Karl Johan Åström: "Adaptation, auto-tuning and smart control," 3rd International Conference on Chemical Process Control (CPC III), Asilomar, California, USA.

Jan 21, 1986. Karl Johan Åström: "Adaptive control systems," NASA, Moffet Field, California, USA.

Jan 23, 1986. Karl Johan Åström: "Adaptive control theory," China Lake, California, USA.

Jan 28, 1986. Karl Johan Åström: "Adaptive systems," CalTech, Pasadena, California, USA.

April 8, 1986. Karl Johan Åström: "Prediktion och styrning av stokastiska processer," (Prediction and control of stochastic processes), Lunds Matematiska Sällskap, Lund University, Sweden.

April 9, 1986. Karl Johan Åström: "Adaptive friction compensation," IEEE International Conference on Robotics and Automation, San Francisco, California, USA.

July 16, 1986. Björn Wittenmark: "Adaptive control—An overview," East China Normal University, Shanghai, China.

July 17, 1986. Björn Wittenmark: "Self-tuning regulators," East China Normal University, Shanghai, China.

July 18, 1986. Björn Wittenmark: "Applications of adaptive control," Shanghai Automation Society, Shanghai, China.

July 21, 1986. Karl Johan Åström: "Adaptive friction compensation in robot drives," DFVLR, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V., Oberpfaffenhofen, München, FRG.

July 21, 1986. Björn Wittenmark: "Adaptive systems in control and signal processing—A report from the workshop in Lund," East China Normal University, Shanghai, China.

July 24, 1986. Björn Wittenmark: "Dual control theory," East China Normal University, Shanghai, China.

Aug 12, 1986. Bengt Mårtensson: "Dynamic high-gain stabilization of multivariable linear systems, with application to adaptive control," SIAM Conference on Linear Algebra in Signals, Systems and Control, Boston, Massachusetts, USA.

Aug 29, 1986. Karl Johan Åström: "Expert control," Introduction to a round table discussion on expert systems in Automatic Control, IFAC Symposium on Large Scale Systems, Zürich, Switzerland.

Sept 9, 1986. Björn Wittenmark: "Adaptive control—An overview," University of Newcastle, Australia.

Sept 19, 1986. Karl Johan Åström: "A perspective on control engineering," Keynote talk, IEEE Workshop on the Challenge to Control, Santa Clara, CA, USA.

Sept 26, 1986. Karl Johan Åström: "Artificial intelligence and automatic control," Introduction to a panel discussion, IEEE Control Systems Society Third Symposium on Computer-Aided Control System Design (CACSD), Arlington, Virginia, USA.

Sept 30, 1986. Rolf Johansson: "Practical problems of adaptive control," (in Swedish), NSF – Norske Sivilingeniørers Førening (Norwegian Engineering Society), Geilo, Norway.

Feb 13, 1987. Karl Johan Åström: "Adaptive control," lecture at the 25th year jubilee of the Engineering Physics Department at Lund Institute of Technology, Lund, Sweden.

March 3, 987. Björn Wittenmark: "Some applications of adaptive control," University of New South Wales, Sydney, Australia.

March 5, 1987. Björn Wittenmark: "Adaptive stability augmentation or how to use a priori knowledge," University of Newcastle, Australia.

May 6, 1987. Karl Johan Åström: "Automatinställning," SattControl, Stockholm, Sweden.

May 20, 1987. Karl Johan Åström: "Expert systems and feedback control," University of Maryland, USA.

May 27, 1987. Björn Wittenmark: "Some applications of adaptive control," University of Newcastle, Australia.

June 4–5, 1987. Karl Johan Åström: "PID-control," "Interconnection of simple regulators," "State feedback and Kalman filters," "Predictive Control," "Autotuning," "Adaptive control." Lectures given in a five days course in mechatronics, organized by PECEE (A European Programme in Continuing Education of Engineers), held in Leuven, Belgium.

June 15–29, 1987. Björn Wittenmark: Minicourse in adaptive control with the following lectures: "Adaptive control—An overview," "Model reference control," "Self-tuning regulators," "Stochastic adaptive control," and "Practical aspects and implementation," University of California, Santa Barbara, California, USA.

July 1, 1987. Karl Johan Åström: "Stochastic control theory," Invited plenary lecture, 1st Int Congress of Industrial and Applied Mathematics (ICIAM '87), Paris, France.

Sept 28, 1987. Karl Johan Åström: "Advanced control methods – Survey and assessment of possibilities," 13th Annual Advanced Control Conference, Purdue University, West Lafayette, Indiana.

Sept 30, 1987. Karl Johan Åström: "Recent advances in theory and practice of adaptive control," School of Mechanical Engineering, Purdue University, West Lafayette, Indiana.

May 27, 1988. Karl Johan Åström: "Towards intelligent control," Douglas Holder lecture at University College, University of Oxford, UK.

May 30, 1988. Karl Johan Åström: "Autotuning, adaptation and expert systems," Course on Application of Advanced Control in the Chemical Process Industries, DTH, Lyngby, Denmark.

June 2, 1988. Karl Johan Åström: Minicourse on Adaptive control theory: 5. "Tools for convergence analysis," University of Oxford, UK.

June 9, 1988. Karl Johan Åström: Minicourse on Adaptive control theory: 6. "Convergence analysis of adaptive algorithms," University of Oxford, UK.

June 10, 1988. Karl Johan Åström: "Stability of model-reference adaptive control systems in the presence of unmodelled dynamics," Department of Electrical Engineering, Imperial College, London, UK.

June 14, 1988. Karl Johan Åström: "Adaptation auto-tuning and intelligent control," Tutorial Workshop on Some Aspects of Intelligent Control, American Control Conference, Atlanta, Georgia, USA.

June 15, 1988. Karl Johan Åström: "Towards intelligent control," invited plenary lecture at American Control Conference, Atlanta, Georgia, USA.

June 17, 1988. Karl Johan Åström: "Robust and adaptive pole-placement," American Control Conference, Atlanta, Georgia, USA.

June 21, 1988. Karl Johan Åström: "Practical experiences of adaptive control," University of Sussex, UK.

June 24, 1988. Karl Johan Åström: Minicourse on Adaptive control theory: 7. "Robustness of adaptive control," University of Oxford, UK.