Automatic Control, LTH -- Past, Present and Future

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Contents

1. Introduction

This report describes the activities at the Department of Automatic Control at Lund Institute of Technology (LTH) over the academic years 1984/85–1988/89. The report is compiled for the special purpose of the evaluation of LTH in the spring 1990. The report follows the outline specified by the Division of Applied Physics (Sektionen för Teknisk Fysik). The report gives a condensed overview of the activities during the last five academic years. The results are given in the form of lists of personnel, degrees, awards, and publications. For more details we refer to our annual reports. We also give a review of the cooperation with other academic institutions and industries, in Sweden as well as internationally. In the report we report the funding situation for the academic year 88/89. Finally a brief description of research plans is given.

Automatic control is a fundamental subject within the area of applied mathematics and it gives the fundamental principles for control and automation. Typical problem areas are mathematical model building, identification, analysis, synthesis, simulation, and implementation. Automatic control has theoretical as well as experimental aspects. The subject is an important part of information technology. The department covers a broad area of research and we have contacts with many departments and industries in Sweden and abroad.

2. Personnel

The undergraduate education in automatic control started at LTH in 1964. The first professor in Lund was Karl Johan Åström, who came to Lund in 1965. The department then had 3 positions. Today the number of employees are 33, of which 11 are funded through external sources. The department has 2 professors, 4 associate professors (högskolelektorer), 1 assistant professor (forskarassistent), 2 secretaries, 4 research engineers (forskningsingenjörer), and 7 teaching assistants (doktorandtjänster) funded by LTH. One visiting professor and 11 research assistants (forskningsassistenter) are funded from external sources. A list of the personnel is given in Appendix A.

3. Funding

The budget for 88/89 is listed in Appendix B. The income for the department is distributed as follows (1 kkr = 1000 SEK):

Source	Amount
FFU (LTH Research)	2311 kkr
GU (LTH Education)	3053 kkr
External funds	4239 kkr
Total sum	9603 kkr

In our accounts we also have 1282 kkr available for purchase of equipment.

The funding situation for 88/89 is normal for the period. The exception is the funds for equipment. During 88/89 we received a donation of 1000 kkr from Wallenbergstiftelsen for purchase of workstations.

4. Education

Undergraduate Courses

Automatic control courses are taught as a part of the engineering curricula in Engineering Physics (F), Electrical Engineering (E), Computer Engineering (D), Mechanical Engineering (M), and Chemical Engineering (K).

During the year 88/89 the following courses were given at the department:

Name of the course (Section)	Number of students
Reglerteknik AK (F, E, D) (Automatic control, linear systems)	226
Reglerteknik AK (M) (Automatic control, linear systems)	112
Processreglering (K) (Automatic Process control)	79
Digital reglering (F, E, D) (Computer controlled systems)	118
Datorimplementering av reglersystem (F, E, D) (Computer implementation of control systems)	31
Processidentifiering (F, E, D) (Process identification)	21
Adaptiv reglering (F, E, D) (Adaptive control)	18

The figures give the number of students that have passed the courses during 1988/89, totally 605 students.

Master Theses

An important part of our education is supervision of master theses. During the period 96 theses were completed by 114 students. Many of the theses are done in cooperation with industries. The theses made at the department

are usually part of our ongoing research or prestudies for new research. The master theses are a good way to recruit graduate students.

Graduate Enrollment and Funding

For the moment we have 17 graduate students at the department. Seven students are funded from teaching assistantships from LTH. One third of their time is allocated to teaching and other departemental duties. Seven students are funded by research grants. Three students are working in industry and are not financed through the department. We don't have any doctoral scholarship (utbildningsbidrag) at the department.

Graduate Program

In the graduate program we have a course requirement of 60 credits (poäng) for the licentiate and 80 credits for the PhD. The thesis normally requires one year for the licentiate and two years for the PhD. We encourage the students to use the licentiate degree as a step towards the PhD degree.

A course normally includes lectures, seminars, and exercises. Some part is often fulfilled as a project or an independent study. The exams are written and/or oral, and sometimes of the "take-home"-type. Some courses are given regularly, while other may be given by guest-professors or related to ongoing research. The students are encouraged to take courses from other departments and other schools. The department of Mathematics has been particularly accomodating to the needs of our students. Graduate courses given over the period 84–89 are listed in Appendix C.

The level of the PhD-thesis is required to be at least the same as for publication in good international journals. The licentiate thesis may contain more preliminary work.

Our students are encouraged to spend some time abroad at other universities. It would be highly desirable to have funds for this. We have also received graduate students from abroad, see Appendix H. To facilitate this we have started to teach some undergraduate and graduate courses in English.

Awarded Degrees

The quality of the research and graduate program at the department is considered to be of high international standard. Since 1970 31 PhD degrees have been awarded and 19 licentiate degrees. Among the persons that have taken their doctoral degree at the department 7 have been appointed full professors and 15 have leading positions in the industry. Degrees awarded during the time 84–89 are listed in Appendix D. During this period 4 PhD degrees and 9 licentiate degrees were awarded.

5. Publications and Awards

The results of the research at the department are spread through publication of books, papers, conference contributions, and personal contacts. This part of our activities is substantial and important. During the last five years the researchers of the department have published 51 papers and given 148 contributions at international conferences. Four books in the areas of stochastic control theory, computer controlled systems, adaptive control, and process controlled have been published by Karl Johan Åström, Björn Wittenmark, and Tore Hägglund. The books are written in English and published by American companies. Two of the books are translated to Japanese, Chinese, Russian, and Spanish. Table 5.1 gives a summary of publications during the years 84-89. A complete list of publications is given in Appendix E. A measure of the good international reputation is the great number of invitations to deliver key note lectures at conferences and to write articles in well-renowned journals.

Both senior and junior members of the department have received awards. Karl Johan Åström has received KTH's stora pris, the Rufus Oldenburger award from the American Society of Mechanical Engineers, the Donald G. Fink Prize from the Institute of Electrical and Electronics Engineers (IEEE), and the Quazza Medal from the International Federation of Automatic Control (IFAC). The Quazza Medal is the highest technical award of IFAC. It is given every third year. Previous recipients are professor J. Coales, Cambridge and professor Ya. Tsypkin, Moscow. Several of our graduate students have received the Asea Master Thesis prize and the SAAB-Scania award. A complete list of the awards is found in Appendix F.

6. Coordination of Education and Research

The department has established a policy of having strong interaction between undergraduate education and research. Several mechanisms are in place to implement this policy. Everyone at the department does both research and

Table 5.1 Summary of publications 84/85–88/89

	84/85	85/86	86/87	87/88	88/89	Sum
Books	1	0	1	1	1	4
Papers	11	8	8	14	10	51
Conference papers	21	24	23	25	55	148
Final reports	7	7	13	9	6	42
Master theses	16	29	15	14	22	96
Internal reports	14	37	48	30	32	161

teaching. All teaching duties are rotated among the members of the department. There is no separation between the different teaching duties. Assistants may lecture and professors may do laboratory instructions. This construction gives us flexibility. It also gives us a robustness, since several persons at the department can give all of our courses.

Another way to create a link between research and education is our external courses. Several of the courses have started as a way to bring research to the industry. By giving the courses for an industrial audience we have got some of our developing costs covered and several of the courses are now given within the engineering degree program. Examples are Adaptive Control and Process Identification. The external courses have also been used to develop new material for existing courses. Examples are revisions of our basic course in automatic control and the digital control course.

7. Cooperation

At the department we have emphasized the importance of having good international and industrial contacts. In this section we want to indicate some of these contacts and means for establishing and maintaining a good network of contacts.

Industrial Cooperation

Automatic control is both a theoretical and experimental subject. To make experiments and earn practical experience we have over the years had close contacts with many industries in Sweden and abroad. The following is a list of industries with which we have had contacts and exchange. We have had longterm contacts with the companies marked with a *.

* ABB
* Alfa-Laval
* Billerud
* Bäckhammar
* Datema
* DuPont

  Ericsson

  First Control
* Fisher Control

  Foxboro
* Gambro

  Gullfiber

  Honeywell

  Hylte Bruk

* IBM
* Kamyr
  Karlshamns Oljefabrik
* Kockum Sonics
* Kockums Marine
* Käppala Reningsverk
* NAF
* Malmö Reningsverk
  Philips
  Rockwool
* Saab
* Satt Control
  SCA
  Shell
  Skoghall
  Sockerbolaget
* SSPA
  Supra
* Sydkraft
  Sypro
* Telemetric
  TetraPak
  Tour & Andersson Innovation
  United Turbine
* Vattenfall
  Volvo
  Åkerlund & Rausing

With some industries like Sydkraft, ABB, Satt, and Kockums Marine we have had a long continuous collaboration, which has included master thesis projects as well as research directly supported by the industry. In some cases staff members have been on leave to work at the industry for longer periods. Sydkraft and Vattenfall have since 1986 been funding a visiting professorship in power systems.

One important way to create new industrial contacts is our external courses. Courses are given 3–4 times a year for 16–20 participants. The lectures in the courses are illustrated through laboratory experiments. Typical areas for the courses are: computer controlled systems, adaptive control, process control, simulation, identification, and knowledge-based control.

We have been working together with many industries on a more long term basis. In this cooperation we have participated in the development of several products. Some examples can be used as an illustration.

Adaptive control has been a research area for the department since the end of the 1960's. Already in 1972 we made practical experiments with self-tuning regulators together with Billerud at the Gruvön Plant. The research with self-tuning controllers resulted in cooperation with ABB. Later under the

management of two of our former students, Gunnar Bengtsson (PhD), and Rolf Syding (MSc) the work resulted in the NovaTune adaptive controller. The development has later been directed by Bo Egardt (PhD). The company First Control has been established by Gunnar Bengtsson and they have developed a new line of adaptive controllers. The research on adaptive control and identification has also resulted in an adaptive autopilot for ships. The work started as a STU project together with Kockums in Malmö. An adaptive controller was developed by Claes Källström (PhD) in a joint research program. Support for product development were given by former students Lars Erik Torelli (MSc), Johannes Eriksson (MSc), Leif Steen (MSc), and Jan Sternby (PhD). This adaptive controller is installed onboard many ships. Further development of ship steering systems have been done at SSPA by Claes Källström (PhD) and Kalle Theorén (MSc).

The ideas of auto-tuning by Karl Johan Åström and Tore Hägglund has been commercialized by NAF and Satt Control under the supervision of Lars Bååth (MSc) and Tore Hägglund (PhD). The autotuner is licensed to Fisher Control in USA. New autotuning ideas and patents are now exploited by High-Tech and TAIAB under the supervision of Anders Wallenborg (Tekn.lic.). Gambro has developed an adaptive controller for dialyzers under the direction of Jan Sternby (PhD). The department has participated in several stages of the project.

Hilding Elmqvist (PhD) started the development of graphical presentation and information zooming as a STU project at the department. Later he joined Satt Control and has developed these ideas into the products SattGraph 1000 and SattLine. Lars Pernebo (PhD) has also participated in the development and the department has contributed with discussions and supervision of master thesis projects.

In 1983 we started work in the area of artificial intelligence (AI). Our approach was to use ideas from AI and expert systems to create new tools for tuning and supervision of control loops. The work started by inviting John Anton, Systems Control, USA, for a graduate course. This initiated master theses and a doctoral thesis work in the area. Through support by STU we have been able to make substantial research and development in the area of expert systems. Karl Erik Årzén (PhD) and Jan Erik Larsson (Tekn.lic.) now participate in an industrial cooperation within the national information technology program IT4. The project is a precompetitive study together with ABB and Satt Control. Karl Erik Årzén is now invited to serve as an editor for the field of expert systems for the journal Automatica. Our work in the field of AI has also stimulated the development at LTH. Under the direction of the department a graduate course was given in 87/88. Jan Erik Larsson has developed and is lecturing the course Applied Artificial Intelligence, which is elective for the undergraduate students in Computer Engineering.

Good computer aided design tools are important for the development of control systems. This has been a research area for the department for a long time. The program packages Simnon, Idpac, and Synpac have been developed at the department. Simnon started as a master thesis by Hilding Elmqvist (PhD). The program was further developed and is now available for mainframes, PC-computers and workstations. These program packages have been sold commercially for many years. Simnon is now licensed to SSPA, where Claes Källström (PhD) is heading the sale and the further development of the program. Simnon has been used in many industries throughout the world.

It is verified, for instance, from General Electric that the use of Simnon and Synpac will considerably shorten the developing time for new control systems.

University Cooperation

We have good contacts with many university departments. In fact many former members of the department in Lund are holding university positions:

LTH	Gustaf Olsson, professor Industrial Automation
	Lars Jensen, professor Building Science
	Jan Holst, associate professor Mathematical Statistics
LiTH	Lennart Ljung, professor
	Torkel Glad, professor
UU	Torsten Söderström, professor
CTH	Bo Egardt, professor
LuTH	Jan Sternby, adjoint professor
Högskolan i Växjö	Mats Lenells, associate professor
Technion, Haifa	Per-Olof Gutman, associate professor

Finally the four associate professor positions at our department are filled with former PhD's from the department: Per Hagander, Rolf Johansson, Lars Nielsen, and Tore Hägglund.

Internationally we have close contacts with most of the major universities in the world within our field of research. Special contacts and exchange of students and researchers are established with many universities. A list of universities with which we have close contacts is given in Appendix G. Several staff members have held university appointments at other universitites. Some of our students have attended courses or participated in research abroad. This activity is, however, strongly limited because of lacking funds. We are trying to encourage visits by foreign researchers. A list of guests, who have visited the department more than a week, is found in Appendix H. The total time of guests is summarized to about 100 man-months for the period 84-89. In Appendix I is given a list of visits that members of the department has done during the period 84–89. Only visits of a month or more are listed.

Many of our contacts are maintained through international organizations and through editorship in journals. For instance, Karl Johan Åström has been the member of the council of the International Federation of Automatic Control (IFAC). Björn Wittenmark is appointed to the Board of Governors for 1990 of the Control System Society of IEEE. Karl Johan Åström is member of the advisory boards for the Laboratory for Information and Decision Systems at MIT and the Systems Research Center at University of Maryland. Per Hagander, Sven-Erik Mattsson, Björn Wittenmark, and Karl Johan Åström are members of different technical committees of IFAC. Karl Johan Åström and Karl Erik Årzén are editors for survey papers and expert systems respectively, and Björn Wittenmark is an associate editor for the journal Automatica, which is one of the most authoritative journals in the field of automatic control. Björn Wittenmark and Karl Johan Åström are editors or members of the editorial board of a number of journals in the field of automatic control.

Several of the members of our department have served as opponents for doctoral and licentiate theses in Sweden and abroad.

8. Facilities and Equipment

Offices and Laboratories

Our offices and laboratories are located in the Mechanical Enginnering building. We are in great need of additional office space. Most of our graduate students are sharing offices. For our immediate need 6 new modules are required. This does not include any expansion of the activities of the department. Another main inconvenience is that our facilities are on three different levels. This is very bad with respect to communications and efficiency. By courtesy of the Division of Mechanical Engineering we have in the recent years been able to extend our laboratory space. This now makes it possible to efficiently run the undergraduate courses, which all includes laboratory work.

Laboratory Equipment

It is a policy at the department that our students should have a strong theoretical base and an engineering ability. A laboratory is a necessity to instill engineering ability. We considered building some pilot plants, but this was discarded for cost reasons. Instead we have built desk-top experiments. Larger experiments are done in collaboration with industries. We have also established a small but extremely competent technical support group (Leif Andersson, Rolf Braun, Tomas Schönthal, and Anders Blomdell). They are responsible for hardware and software support at the department as well as support in industrial experiments.

The current desk-top experiments include:

Electrical servo

Water tanks

Ball and beam processes

Robot simulator

Production line

Heat transfer

We have further a robotics laboratory and a hydraulics laboratory. In the robotics laboratory an industrial robot, Asea Ib-6, is used for experiments and research. In the hydraulics laboratory we have a hydraulic servo with an inverted pendulum.

The combination of desk-top experiments, laborations, and industrial experiments, under guidence of the technical support staff, have proven a very useful tool in providing our students with engineering ability.

Computer Facilities

The total computer capabilities of the department are as follows:

- **A Sun Workstation** network containing two file servers, a Sun 3/180 and a Sun 4/390 with a total of 1.8 GB disk. We have a number of workstations including 11 Sun 3/50 with 8 MB memory, 1 Sun 3/110 with 16 MB memory and color graphics, and 4 SparcStation 1.

- **Vax-11/780** with 10 MB memory and 750 MB disk. The most important programs are Pro-Matlab, Macsyma, CtrlC, TEX, Lisp and our own packages Simnon and Idpac.

- Fourteen **IBM-AT** or compatibles with 640 kB memory and 20 MB disk. They have analog input and output channels (4 or 16 channels in and 2 or 8 channels out) and also some digital I/O. The main use of these computers is for real time control, both in formal lab exercises and projects in the undergraduate courses, and also in research projects by graduate students and faculty. The programming is done almost exclusively in Modula-2, and a library containing a real time kernel and real time graphics has been developed. This library has reached such a state of maturity that researchers wishing to perform a control experiment can concentrate on the control algorithm and let the library take care of the problems of real-time programming. The achievable sampling rates are up to 100 Hz.

  The same computers are also used for control design. Interfaces are provided to PC-Matlab and to our own new PC-Simnon, so that parameters obtained in a design can be transferred both to Simnon for simulation using a nonlinear model, and to the Modula-2 system for control of the real process.

  The PC-Simnon is very easily available and has grown to a great success.

- Four **Macintosh Plus**, used for text processing and for creating figures and drawings for the technical reports. A special program on the Vax enables the inclusion of drawings produced on the Macintosh directly into TEX documents produced on the Vax.

- Two **Macintosh II** intended for development of control engineering software in a Macintosh environment.
- An **Iris Workstation** with 6.5 MB memory, 150 MB disk and powerful color graphics with 1024×780 pixels and 24 bitplanes. This computer is used mainly in the CACE project described elsewhere in this report.

- **A Symbolics 3650 Lisp Machine**

The Vax, the Suns, the Iris, and the Symbolics are connected in a computer network (TCP/IP and ethernet). The Macintoshes are connected in an Apple Local Talk network, and these two networks are connected via a Kinetics FastPath bridge.

Our main goal concerning the computer equipment is today to develop an integrated computer system based on workstations. This system will replace the Vax-system as our main computer facility.

9. Research Activities

This section gives a summary of the current research activities of the department. The space only allows short descriptions of the different areas. Research at the department concerns both theory and applications. The main research areas are:

Adaptive control
Expert control
Computer aided control engineering
Robotics and sensory control
Power systems
Biotechnology processes
Biomedical systems
Numerical methods

The areas are highlighted below.

Adaptive Control

Researchers: Karl Johan Åström, Björn Wittenmark, Rolf Johansson, Tore Hägglund, Michael Lundh, Kjell Gustafsson, Bo Bernhardsson, Per-Olof Olsson, Lars Rundqwist

During the last years the following problem areas in adaptive control have been investigated:

- Analysis of robustness of adaptive systems
- Analysis of auto-tuning
- Multivariable adaptive control

New emerging research problems have also arisen. In this context we would in particular like to mention robust adaptive control and the relations between adaptive control and AI.

Adaptive control research is currently focused on the use of parametric models. The parameters can typically be coefficients in a transfer function model. This approach has proven very successful. It is easy to generate recursive parameter estimators, and there are control design techniques available. The approach has, however, two significant drawbacks, first it is necessary to assume a model structure, secondly the parametric approach is not well suited to capture model uncertainty. A nonparametric approach can be developed using frequency domain concepts. This has been pursued for simple systems. The key idea is to determine and track critical points on the Nyquist curve of the process.

The main thrust of the research is now to develop frequency response approaches to adaptive control. A key problem is to develop suitable design methods that can be used on line. A first step in this direction is methods based on measurements of the transfer function for a low number of frequencies. This knowledge can be used to design a low order controller based on approximation theory.

Some work on multivariable adaptive control has been done. Adaptive control of a robot manipulator motion designed by methods of Lyapunov theory has been developed. The methods exploits the physical structure of the system as well as the natural energy interpretations of the Lyapunov functions used in the design.

Expert Control

Researcher: Karl-Erik Årzén, Karl Johan Åström, Jan Erik Larsson, Per Persson, Stéphane Sallé, Tore Hägglund

Research on expert control has been funded by STU since 1985. The goal of expert control is to extend the range of conventional controllers by encoding general control knowledge and heuristics concerning controller tuning and adaptation in a supervisory expert system. We are here cooperating with professor C.C. Hang, Singapore. An important part of the project is architectures for real-time on-line expert systems. The department participates in the IT4 project "Knowledge-based Real-time Control Systems" together with Asea Brown Boveri and SattControl. The aim of this project is the integration of knowledge-systems and conventional distributed control systems. The concept is based on a object-oriented multi-level, multi-view model of the process. The UHT sterilization process Steritherm from Alfa Laval is used as a demonstrator.

Computer Aided Control Engineering (CACE)

Researchers: Sven Erik Mattsson, Karl Johan Åström, Mats Andersson, Bernt Nilsson, Dag Brück, Tomas Schönthal

This area has been financed by STU within the research project "Computer Aided Control Engineering, CACE". The efforts has been focused on tools for model development and simulation.

The main result is a proposal for a kernel for model representation. The kernel may serve as a central model data base in an integrated environment for model development and simulation. The CSSL definition from 1967 has had a profound impact on simulation and has served very well for over 20 years. It is now time to capitalize on the enormous development of information technology and reconsider the foundations of model representation. The proposal is an effort in this direction. If we could agree upon a common set of ideas we may lay the foundation to a new standard. The proposed kernel supports a modularized and object oriented representation of models to allow flexible and safe reuse of model components. The model developer may supply extra information which is used for automatic consistency analysis to check for unintended abuse of models. The kernel can allow any logical and mathematical framework such as differential-algebraic equations, difference equations, etc. to describe behavior, but a basic idea is that behavior descriptions should be declarative and equation based. The kernel allows integration of different customized user interfaces. A prototype of the kernel is implemented in Common Lisp and KEE. A new STU-supported project to implement the kernel in C++ has been started. The project has also included an application study focusing on modeling of chemical processes.

Robotics and Sensory Control

Researchers: Lars Nielsen, Ola Dahl, Klas Nilsson

A laboratory for robotics and sensory control has been initiated. The experimental work is centered around an Asea Irb-6 robot. Hardware interfaces have been developed around new chips for resolver to digital conversion. Other experimental setups are a separate Asea Irb-6 DC-servo motor with the same interfaces, and setups used for different versions of a DC-servo developed at the department. Among these setups there is a robot simulator based on two such DC servos connected via a signal processor based on TMS 32010. The software used is based on the language Modula-2 and on a real time programming environment developed at the department. The hardware is IBM-AT computers. A VME-based system connected to a SUN workstation is under development.

Using this environment a number of projects and prototype systems have been tested in research, education, and master theses work. The main research project has been path following. The goal is to have efficient specification and generation of fast robot motions along a geometric path. Typical applications are gluing, arc welding, and laser cutting. Control algorithms for adjustment of a nominal velocity profile along the path have been developed and tested in simulations and experiments. Other projects include identification of robot parameters from real data, experiments with adaptive control of the Asea Irb-6 robot, implementation of robot control programs, and automatic generation of code for control algorithms.

The research also includes results in image analysis, where projective geometry has been utilized. In the robotics project we collaborate with professor Caver Mead at California Institute of Technology.

Power Systems

Researcher: Magnus Akke, Bo Eliasson, Karl Johan Åström, Björn Wittenmark

A guest professor in power systems has been supported by Sydkraft and Vattenfall. The following has been working in this position:

David Hill, University of Newcastle

Rod Bell, Macquarie University

Neville Rees, University of New South Wales

The research in power systems has also been supported by Statens Energiverk (STEV). In close contact with Sydkraft work been done in modeling of units in thermal plants. The intention is to develop a model library that can be used in different studies. For instance, simple drum-boiler models has been developed.

The second area in power systems is power system stabilization. Self-excited low frequency power oscillations in large power systems may jeopardize the operation of the systems. The problem is to model the large systems and to decide where to place the damping equipment. The design methods are tested on models of the Nordic power system. The load model has a great influence on the resulting controller. Voltage dependent loads have been investigated in cooperation with professor David Hill, University of Newcastle, Australia.

Further work on siting and tuning of power system stabilizers has been done and the methods are demonstrated on a 244 machine model of the Nordic power system.

Biotechnology Processes

Researchers: Per Hagander, Jan Peter Axelsson

A joint project with the Department of Biotechnology, Chemical Center, on control in biotechnology processes has been funded by STU since 1983. The purpose of the work is to investigate the possibilities for process control using direct measurements of substrate, product and intermediates in the processes. Newly developed biosensors have been applied to fed-batch production of baker's yeast. Here measurement of ethanol concentration gives a sensitive indication of the metabolic state of the cells. Identification experiments are performed in closed loop, and parameter estimation is done for models with partially known dynamics. Some optimal control problems are also formulated and investigated using nonlinear control theory.

A new direction of the work is started up. The bacteria *Pseudomonas Cepacia* is grown on the toxic substrate salicylate to produce the enzyme salicylate hydroxylase. The enzyme is used in clinical chemistry to determine salicylate in blood samples. The purpose of the work is to control the substrate addition to be enough for growth without any adverse effect from its toxicity. A spectrophotometric sensor is developed, and experiments are performed using PI-control around a basic substrate flow scheme.

A cooperation with ETH has started in the biotechnology research area.

Biomedical Systems

Researchers: Rolf Johansson in cooperation with Dr. Måns Magnusson (Department of Oto-Rhino-Laryngology, Lund University Hospital)

Two projects treat estimation of parameters and modeling of human posture dynamics. The work is sponsored by the Swedish Medical Research Council (MFR) and Söderbergs Foundation. The stability investigation is made with induced body sway by galvanic or vibratory stimuli followed by analysis with application of methods from signal processing and control theory. The goal is to find parameters that describe the human ability to maintain posture. The methods developed are intended for use in diagnosis and rehabilation of human balance disorders.

Numerical Methods

Researchers: Sven Erik Mattsson, Kjell Gustafsson. Cooperation with Gustaf Söderlind (ITM, Stockholm)

When implementing a numerical algorithm it has to be equipped with supervisory code that acts as a safety net. This code chooses parameters and handles exceptional cases in such a way that the algorithm runs smoothly and produces a correct result. Using analogies from automatic control the supervisory code can be regarded as a controller with the numerical algorithm

as the controlled process. The controller tries to make the system produce a sufficiently accurate solution with a minimum amount of calculations. In the case of numerical integration of ordinary differential equations the controller measures an estimate of the integration error and uses it to decide upon the stepsize to use in the next integration step. Viewing the system as a dynamic control system provides insight not supplied by the standard static asymptotic analysis in the current numerical analysis literature.

The control system viewpoint of stepsize selection has been exploited in a project partly sponsored by STU. A new improved controller was designed for explicit Runge-Kutta methods. The new controller has been implemented in one of the integration routines in the simulation package Simnon with very good results.

10. Plans for Future Research

This section gives an outline of what areas may be of interest over a time period of 1–5 years. The review should be regarded as a goal to aim for rather than a definite plan. The different current research areas will be discussed.

Intelligent Control

Within this area we include and combine the research in adaptive control, knowledged-based control, and expert systems. We believe in an integration of these different aspects of a control system. Rather than having one layer for loop controllers and another layer for production planning we see a tendency to combine and integrate. This will make it possible to improve the quality of the control and the supervision of the total plant.

Adaptive feedforward control is now being investigated and new results will probably be possible to be reported within the next 1–2 years. One line of development within adaptive control is to construct robust adaptive controllers. This is pursued along two directions. First we are developing a set of robust algorithms for implementing self-tuning and model reference adaptive controllers. Special emphasis is put on the implementation aspects such as supervision of the estimator and numerical robustness in the design algorithms. This work will probably be completed over the next 2–3 years. This research will also include how to handle a priori knowledge in adaptive systems. Secondly a more longtime research line is to convert new robust design methods into adaptive robust design methods, i.e. to adapt the algorithms to the case when the parameters are uncertain and when the uncertainty is changing with time. This requires new methods for estimation that are better suited for the robust design methods than the parametric model estimators that are used today. Adaptive feedforward control is now being investigated and new results will probably be possible to be reported within the next 1–2 years.

A more theoretical line of research in adaptive control is a general approach to direct and indirect adaptive controllers. Different algorithms and

their properties will be analyzed with respect to stability and possible convergence points. This research has a time horizon of 2–5 years.

The relation between optimal and adaptive systems is an interesting and promising research field of much interest for applications. Both optimization of adaptive control and adaptation are of interest as the means to find optimal solutions. Experiences of adaptive control research may also prove useful for the research emerging in the area of artificial neural networks. Some preliminary results with general application to applied motion control support the interest of further efforts in this area.

Autotuning has been a successful development at the department. In this area we intend to develop an intelligent controller that combines control and diagnosis. The control algorithm can be either of PID type or a more general controller structure. This type of controller will then be developed into a multiloop controller with an built-in loop design advisor, which will help the operator to determine a suitable configuration. The first phase has a time horizon of 2–3 years and the second phase 4–6 years.

The relay autotuner forms the basis for the expert control systems designed at the department. Design based on dominant pole design has been studied for some time in connection with autotuning. This research will be finished and reported during the next year. Since the autotuning project started at the department, we have gained lots of experience concerning design of PID controllers. We plan to build a simple and robust expert control system where our knowledge about PID design is included. The system will also include procedures for supervision and diagnosis of the control. These procedures will e.g. provide information about malfunctions in sensors, actuators, and valves, check the noise characteristics and possible nonlinearities. The goal for the project is to provide a robust system that could be implemented in the next generation of single loop controllers. Within one year we will complete the specifications of the system, including derivation of diagnosis and detection procedures, and the implementation will be started. The total time for the project is 4–5 years.

One extension of the adaptive procedure used in e.g. the relay autotuners is to use a FFT to obtain the frequency response at more than one frequency. Then design procedures like those derived in the PhD thesis by Mats Lilja could be used. As more experience is obtained from the industrial applications, future directions of the adaptive control projects will probably show up.

The work on knowledge-based control systems currently performed in cooperation with ABB and SattControl under the IT4 program will continue. The long term goal for this work is the development of distributed control systems that integrates conventional algorithmical control and monitoring techniques with knowledge-based techniques. Important areas of research are knowledge-based systems for real-time operation, object-oriented process and control system modeling, model-based techniques for fault diagnosis, and alarm analysis that combines quantitative and qualitative models, and fuzzy rule-based control. The time horizon for this research is 2–5 years.

Design Methods

During the next year the theoretical activity in control system design for linear systems will continue. Work has started on the formulation of nice H^∞-problems, and the strong stability work might grow in that direction.

In the area of synthesis methods we expect to report on new results for anti-reset windup for different controller structures during the coming year. The work involves cascade as well as multivariable systems.

Most control research projects have been focusing on the controller design in the "simple feedback loop". When a new process control plant is to be installed, this is not the major problem. The major problem is the question of how to configure the instrumentation, i.e. how to combine measurement signals and control signals. There are some methods that provide guidance rules for this problem available, e.g. the relative gain array. Over the next five years we plan to finish a project on configuration of process control instrumentation.

Computer Aided Control Engineering

An important activity during 1990 will be to carry out the STU-supported project to develop and implement in C++ a kernel for model development and simulation of continuous time models. Our research results will be generally available. The kernel can serve as a basis for development of commercial products. The next natural step in spreading the new ideas and methods is joint application projects with developers and users of CACE tools. The kernel will be useful in these projects.

An application project together with Sockerbolaget and funded by STU under the DUP project to model sugar crystallization has been started and will be finished in 1–2 years.

The application projects can allow us to tune the tools and to create new special tools and customized user interfaces for different applications. However, the earlier projects have also identified a number of fundamental problems which are very interesting. The kernel supports models described by differential-algebraic equation systems. Unfortunately, today's numerical solvers are not able to solve the type of problem referred as high index problems. Recently we have developed a combined symbolic and numeric approach, which seems to be promising. We have started a close cooperation in this area with Gustaf Söderlind, the new professor in numerical mathematics, LU.

The problem of describing and supporting discrete event features in continuous time modeling are fundamental. In control engineering the models are typically differential-algebraic equation systems, but there is an emerging interest to deal with discrete events to be able to model batch processes, malfunctions and asynchronous supervisory and control systems. Another fundamental problem is databases. We need them to store models, parameter data, measurements, results of calculations etc. Database tools can handle a large set of independent data efficiently, but in CACE the amount of data is moderate, but the relations are complex. Object oriented databases is a promising approach.

CACE is a very important research area and will so be for a long time. We have here only indicated some interesting and important problems, but there are research needs in the whole spectrum from fundamental and theoretical problems to applications. CACE is an interdisciplinary area. We have a very well established contact net with research groups and developers.

Robotics and Sensory Control

The research will continue along the existing lines of development. The problems studied have relevance in practice and promising results have been obtained. Path following algorithms will be further developed, the computer science aspects will be investigated in the laboratory system, and new theory based on projective geometry will be used for different calibration problems e.g. hand-eye-calibration. There are also a number of interesting problems in nonlinear and adaptive control of robots.

Power Systems

Power systems has been an application area for the department over many years. During the last four years we have studied power system stabilization. This work has been done within the framework of the guest professorship sponsored by Sydkraft and Vattenfall. This work will be continued within the coming year.

A long-term research area within power systems is the development of a model library for different units in power systems. Models for boilers, generators, nets, and controllers are available. It is, however, of great interest to adapt the different models to each other and to be able to use them in different combinations. The results of the CACE project can be used to develop and refine different types of models. This is a work that will be continued for 2–3 years.

Biotechnology Processes

The controlled salicylate fermentations have recently started to become reliable and an interesting model-building work is about to start. From the yeast work two lines of research are currently pursued. In the fed-batch yeast production it was found that a special purpose adaptive controller might help to increase the robustness necessary in case of longer measurement time-delays. The stability region of that controller is currently under investigation. Another nonlinear control problem grew out of the continuous ethanol experiments. Some of those results are analyzed theoretically and should result in a publication for a control journal.

In five years time there is no intention to stop the biotechnology work, but the intensity and direction is yet unclear. The current experience is that biotechnology is a field with many control problems of substantial general interest, which might also promote theoretical progress.

Biomedical Systems

Major efforts during the next few years will be directed towards an effective quantitative description of vertigo and human postural control and a characterization of the sensory integration as well as the specific influences of each sensory subsystem, i.e. the visual, vestibular, and somatosensory subsystems. Such work is highly motivated by the diagnostic needs in neurology and is a

prerequisite for classification of many balance disorders. A major theoretical problem in this context is to develop adequate methods of system identification for application to adaptive systems.

A natural second step is to use the clinical and analytic experiences of the present research for rehabilitation purposes. An interesting possibility of rehabilitation and increased mobility is to stimulate the muscles of disabled patients with so called functional neuromuscular stimulation. Such ideas presuppose an adequate strategy of adaptive motion control both for individual adjustment and to compensate for problems of muscle fatigue.

11. Summary

The report gives a summary of the activities at the Department of Automatic Control at LTH. The limited space only allows brief descriptions of the different activities. Further details can be obtained from the list of publications given in Appendix E. We predict that the size of the department will be the same as today over the next 2–4 years. The current research areas together with past and predicted results make us confident that we can continue to make significant research in several areas of automatic control.

A. List of Personnel

The following list shows the status of July 1, 1989.

Professorer (Professors)
Karl Johan Åström
Björn Wittenmark

Högskolelektorer (Associate professors)
Per Hagander (100% GU)
Tore Hägglund (100% GU)
Rolf Johansson (100% GU)
Lars Nielsen (100% FFU)

Forskarassistent (Research associate)
Sven Erik Mattsson

Forskningsingenjörer (Research engineers)
Leif Andersson
Anders Blomdell
Rolf Braun
Tomas Schönthal

Forskningsassistenter (Research assistants, External funds)
Magnus Akke
Mats Andersson
Jan Peter Axelsson
Bo Bernhardsson
Dag Brück
Anders Hansson
Jan Eric Larsson
Bernt Nilsson
Klas Nilsson
Per-Olof Olsson
Karl-Erik Årzén

Doktorandtjänster (Teaching assistants)
Ola Dahl
Kjell Gustafsson
Ulf Holmberg
Mats Lilja
Michael Lundh
Per Persson
Lars Rundqwist

Institutionssekreterare (Secretaries)
Eva Dagnegård (part time)
Eva Schildt
Agneta Tuszynski (part time)

Assistent (Technical drawings)
Britt-Marie Mårtensson

Visiting Scientists

Stéphane Sallé
Laboratoire d'Automatique de Grenoble
ENSIEG, Grenoble, France
(From 13 February 1989)

Claire Valentin
Laboratoire d'Automatique de Grenoble
ENSIEG, Grenoble, France
(From 31 March 1989)

B. Funding

This appendix gives an overview of the funding for 1988/89. This year is comparable with the other years in the period 1984–1989. The exception is the funds available for equipment. During 1988/89 we received a donation of 1000 kkr from Wallenbergstiftelsen for purchase of workstations.

All figures are given in kkr (= 1000 SEK)

FFU (Research)	Positions	1865	
	Running costs	446	2311
GU (Education)	Positions	2567	
	Running costs	486	3053
External			
STU		2508	
STEV		200	
Sydkraft/Vattenfall		150	
Software sales		700	
IT4		488	
Industrial courses		193	4239
			9603
Funds available for equipment			
UUH		282	
Wallenbergstiftelsen		1000	

C. Graduate Courses

The following graduate courses have been given during July 1984 – June 1989.

Linear systems, 8p (Per Hagander)	fall 1984
Implementation of fast digital control systems, 4p (H. Hanselmann)	Jan 1985
Nonlinear systems and stability theory, 6p (Matz Lenells)	spring 1985
System identification, 8p (K. J. Åström)	fall 1985
Lisp, 2p (K. E. Årzén)	Dec 1985 – Jan 1986
Linear systems, 10p (P. Hagander)	fall 1985 – spring 1986
Introduction to biotechnology, 2p (P. Hagander)	spring 1986
Adaptive control, 6p (K. J. Åström)	spring 1986
Computer Aided Control Engineering CACE, 6p (K.J. Åström, S.E. Mattsson, P. Hagander)	fall 1986
Nonlinear control systems, 8p (B. Mårtensson)	spring 1987
Implementation of adaptive systems, 5p (K. J. Åström)	spring 1987
Linear systems, 10p (P. Hagander)	fall 1987
AI-programming, 6p (W. Kreutzer, K. J. Åström)	winter 1987-88
Synthesis, 8p (K. J. Åström, P. Hagander)	spring 1988
Applied expert systems, 4p (K. J. Åström)	spring 1988
Robustness and adaptation in nonlinear control, 4p (J. J. Slotine)	August 1988
Algebraic system theory, 5p (P. Hagander)	fall 1988
Computer controlled systems, 4p (B. Wittenmark)	spring 1989

D. Doctor and Licentiate Degrees

Doctor Degrees

Nielsen, Lars: Simplifications in Visual Servoing	1985-10-18
Mårtensson, Bengt: Adaptive Stabilization	1986-04-04
Årzén, Karl-Erik: Realization of Expert System Based Feedback Control	1987-11-06
Axelsson, Jan Peter: Modelling and Control of Fermentation Processes	1989-05-19

Licentiate Degrees

Mårtensson, Bengt: The Order of any Stabilizing Regulator is Sufficient a Priori Information for Adaptive Stabilization	1985-05-03
Rundqwist, Lars: Self-tuning Control of the Dissolved Oxygen Concentration in an Activated Sludge System	1986-05-28
Persson, Per: An Expert System Interface for IDPAC	1987-03-20
Wallenborg, Anders: Control of Flexible Servo Systems	1987-05-14
Holmberg, Ulf: Adaptive Dissolved Oxygen Control and On-Line Estimation of Oxygen Transfer and Respiration Rates	1987-05-26
Larsson, Jan Eric: An Expert System Interface for IDPAC	1988-03-21
Gustafsson, Kjell: Stepsize Control in ODE-Solvers Analysis and Synthesis	1988-05-31
Akke, Magnus: Power System Stabilizers in Multimachine Systems	1989-02-27
Dahl, Ola: Torque Limited Path Following by On-Line Trajectory Time Scaling	1989-05-26

E. Publications 84–89

Books

1984–85

Åström, K. J., and B. Wittenmark (1984): *Computer Controlled Systems–Theory and Design*, Prentice-Hall Inc., Englewood Cliffs, N. J. 07632.

1986–87

Åström, K. J., and B. Wittenmark (Eds.) (1986): "Adaptive Systems in Control and Signal Processing 1986," *Proc.2nd IFAC Workshop, Lund, Sweden*, Pergamon Press, Oxford.

1987–88

Åström, K. J., and T. Hägglund (1988): *Automatic Tuning of PID Controllers*, Instrument Society of America, Research Triangle Park, NC, USA.

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Åström, K. J., and B. Wittenmark (1989): *Adaptive Control*, Addison-Wesley, Reading, MA, USA.

Published Papers

1984–1985

Andersson L., P. Hagander, G. Hall, S. Jahnberg, and K. J. Åström (1985): "Programkonstruktion med Ada – en tillämpningsstudie," *Publication Mekanresultat 85006, Sveriges Mekanförbund.*

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Wittenmark, B, and K. J. Åström (1984): "Practical issues in the implementation of self-tuning control," *Automatica*, **20**, 595–605.

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1985–1986

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control for windmills," *Proc 2nd IEEE Control Systems Society Symp on Computer-Aided Control System Design (CACSD)*, Santa Barbara, California.

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Southampton, UK.

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Hang, C. C., and K. J. Åström (1987): "Practical aspects of PID auto-tuners based on relay feedback," Report TFRT-7370.

Hang, C. C., and K. J. Åström (1987): "Refinements of the Ziegler-Nichols tuning formula for PID auto-tuners," Report TFRT-7371.

Johansson, R. (1988): "Stochastic stability of direct adaptive control," Report TFRT-7377.

Johansson, R. (Ed.) (1988): "Processidentifiering. Projektarbete hösten 1987," (Process identification. Project work Autumn 1987), Report TFRT-7384.

Johansson, R., and E. Zettergren (1988): "A smooth D/A-converter for robotic applications," Report TFRT-7374.

Johansson, R., M. Magnusson, and M. Åkesson (1987): "Identification of human posture dynamics," Report TFRT-7373.

Kreutzer, W. (1987): "An exercise in system representations," Report TFRT-7369.

Kvist, P., and H. Ruijter (1988): "An adaptive autopilot with feedforward compensation for wave disturbances applied to ship steering," Report TFRT-7387.

Lundh, M. (1988): "A TOOLBOX for discrete time design and on-line control," Report TFRT-7382.

Lundh, M. (1988): "Source code for TOOLBOX – Version 5.2," Report TFRT-7385.

Lundh, M. (1988): "Calculation of a real sorted Schur decomposition," Report TFRT-7392.

Mattsson, S. E., and K. J. Åström (1988): "The CACE project – Steering committee meeting 1987-11-25," Report TFRT-7375.

Mattsson, S. E., K. J. Åström, D. Brück, and T. Schönthal (1987): "A trip to the University College, Swansea, and the Central Electric Generating Board, Gloucester," Report TFRT-8045.

Nilsson, B. (1988): "A small system-structuring system in scheme," Report TFRT-7379.

Rundqwist, L. (1988): "Självinställande reglering av syrehalten i luftningsbassänger på Käppalaverket – Programdokumentation," (Self-tuning control of dissolved oxygen concentration in aerators at Käppala sewage works – Program documentation), Report TFRT-7383.

Rundqwist, L. (1988): "Övningar och laborationer i Datorer i reglersystem," (Exercises and laboratories in Computers in control systems), Report TFRT-7386.

Rundqwist, L. (1987): "Illustrations in TEX documents," Report TFRT-7372.

Rundqwist, L. (1988): "En laboration i direkt självinställande reglering," (A laboratory in direct self-tuning control), Report TFRT-7388.

Wallenborg, A., and K. J. Åström (1988): "Limit cycle oscillations in high performance robot drives," Report TFRT-7376.

Wittenmark, B. (1987): "Travel report from Australia and China," Report TFRT-8046.

1988–1989

Andersson, L. (1989): "Command decoding in Modula-2," Report TFRT-7413.

Andersson, L. (1989): "A Modula-2 real-time scheduler – Use and implementation," Report TFRT-7414.

Andersson, L. (1989): "Compact TEX," Report TFRT-7422.

Andersson, M. (1989): "Omola – An object-oriented modelling language," Report TFRT-7417.

Axelsson, J. P. (1989): "Flow-rate control of a continuous stirred tank reactor – Start-up and large disturbances," Report TFRT-7420.

Årzén, K. E. (1988): "An architecture for expert system based feedback control," Report TFRT-7399.

Årzén, K. E. (1988): "Remarks and suggestions concerning G2 version 1.1," Report TFRT-7409.

Åström, K. J., and T. Hägglund (1988): "A new auto-tuning design," Report TFRT-7398.

Åström, K. J., and R. D. Bell (1988): "Simple drum-boiler models," Report TFRT-7402.

Åström, K. J., C. C. Hang, and P. Persson (1988): "Heuristics for assessment of PID control with Ziegler-Nichols tuning," Report TFRT-7404.

Åström, K. J. (1989): "Assessment of achievable performance of simple feedback loops," Report TFRT-7411.

Brück, D. (1988): "A foreground/background real-time scheduler for the IBM AT," Report TFRT-7393.

Brück, D. (1988): "Modelling of control systems with C++ and PHIGS," Report TFRT-7400.

Brück, D. (1989): "Experiences of object-oriented development in C++ and InterViews," Report TFRT-7418.

Brück, D. (1989): "Scones – An interactive block diagram editor for Simnon," Report TFRT-7423.

Dahl, O. (1989): "Generation of structured Modula-2 code from a Simnon system description," Report TFRT-7416.

Dahl, O., and L. Nielsen (1989): "Torque limited path following by on-line trajectory time scaling," Report TFRT-7415.

Gustafsson, K., and B. Bernhardsson (1988): "Implementation of a control strategy for an inverted pendulum," Report TFRT-7405.

Iglesias, P. A. (1989): "On the use of robust controllers in adaptive control," Report TFRT-7419.

Johansson, R. (1988): "A new principle for ultrasonic monitoring of blood flow," Report TFRT-7394.

Johansson, R. (1988): "Stability problems of adaptive robot control ad modum Slotine and Li," Report TFRT-7397.

Johansson, R. (1988): "Adaptive control of robot manipulator motion," Report TFRT-7401.

Johansson, R. (1989): "Quadratic optimization of motion coordination and control," Report TFRT-7425.

Larsson, J. E. (1988): "MESS – A minimal expert system shell," Report TFRT-7380.

Mattsson, S. E. (1988): "The CACE project – steering committee meeting 1988-06-01," Report TFRT-7395.

Mattsson, S. E. (1989): "The CACE project – Steering committee meeting 1988-11-23," Report TFRT-7412.

Murphy, S. (1988): "On the Cartesian control of orientation and force for robotic manipulators," Report TFRT-7396.

Nilsson, K., and M. Andersson (1988): "Parametrisk identifiering av robotdynamik," (Parametric identification of robot dynamics), Report TFRT-7410.

O'Young, S. D., J. Hope, K. J. Åström, and I. Postlethwaite (1988): "A comparative study and performance assessment of H^∞," Report TFRT-7403.

Ruijter, H., and L. Nielsen (1988): "A survey of robotics in rehabilitation applications," Report TFRT-7406.

Ruijter, H. (1988): "Teknisk dokumentation av arbetet med UMI-RTX robot," (Technical documentation of the work with the UMI-RTX robot), Report TFRT-7404.

Rundqwist, L. (1988): "Experiences of self-tuning control of an activated sludge process," Report TFRT-7408.

F. Awards 84–89

1985–1986

Karl Johan Åström received KTH's stora pris ur 1944 års donation (The Great Prize from the Royal Institute of Technology) in 1985. This year he was also awarded the Rufus Oldenburger medal from the American Society of Mechanical Engineers "in recognition of technical contributions to the theories of system identification and adaptive control, development of methods and software tools for computer-aided control system design, and innovation and leadership in engineering education and application of control engineering in industry".

Tore Hägglund and Karl Johan Åström received the award "Innovation Cup 1985" sponsored by Skandia and Dagens Industri. Their contribution was "Automatic tuning of digital controllers".

Ola Dahl received the prize Asea Master Thesis 1985 for the master thesis "Image processing techniques for ash line detection".

Jan Eric Larsson received the Bo Rydin prize for best master thesis 1985. The name of the work was "An expert system interface for Idpac".

1986–1987

In 1986 Karl Johan Åström was awarded the Chester Carlsson Medal in information science from IVA in Stockholm.

Kjell Gustafsson received the SAAB-Scania award for graduate students at the SAAB-Scania shareholders' meeting in the spring 1987.

1987–1988

Karl Johan Åström received the Giorgio Quazza Medal at the IFAC Triennial International World Congress in Munich in July 1987. He was awarded the degree Docteur Honoris Causa from l'Institut National Polytechnique de Grenoble on November 20, 1987. In November 1987 he received the prize as the best EFD teacher for the academic year 86/87 from the EFD Educational board, and in June 1988 he obtained a best presentation award at the American Control Conference in Atlanta, Georgia.

Kjell Gustafsson received the Gene H. Golub Prize, best undergraduate presentation award at SIAM Nordic Section Meeting, 26–27 May, 1988, Bergen.

Erik Mårtensson received the prize Asea Master Thesis 1987 for the master thesis "Active damping of oscillation modes in a robot arm".

Per Persson received the SAAB-Scania award for graduate students at the SAAB-Scania shareholders' meeting in May 1988.

Magnus Akke received the Sydkraft energy research award for his licentiate thesis in June 1989.

Karl Johan Åström received the 1989 Donald G. Fink Prize Paper Award for his technical paper "Adaptive Feedback Control", published February 1987 in the Proceedings of the IEEE. The award was presented at the IEEE Conference on Decision and Control in Tampa, Florida, December 1989.

Ola Dahl received the SAAB-Scania award for graduate students at the SAAB-Scania shareholders' meeting on April 28, 1989.

Rolf Johansson received the award "Innovation Cup 1988" sponsored by Skandia and Dagens Industri. His contribution was "Adaptive control of robot manipulator motion".

G. International University Contacts

In this appendix is a listing of universities with which we have close contacts.

Scandinavia

Danmarks Tekniska Högskola
Norges Tekniska Högskola
Tekniska Högskolan i Helsingfors
Åbo Akademi
Ålborg Universitet

Europe

Bremen University
Cambridge University
C.N.R.S./E.S.E. Gif-sur-Yvette
Czechoslovatic Academy of Sciences
Darmstadt Technische Hochschule
Delft University
Eindhoven University
E.N.S. Grenoble
ETH
Hariot-Watt University
Hungarian Academy of Sciences
Imperial College
INRIA
München Technische Universität
Royal Military College of Science
Ruhr Universität
University of Barcelona
University of Florence
University of Glasgow
University of Groningen
University of Hannover
University of Louvain
University of Manchester
University of Oxford
University of Paderborn
University of Rome

University of Strathclyde
University of Sussex
USSR Academy of Sciences

North America

Arizona State University
Brown University
California Institute of Technology
Carnegie Mellon University
Case Western Reserve University
Cornell University
Harvard University
McGill University
MIT
Queen's University
Renssellaer Polytechnic Institute
Stanford University
University of British Columbia
University of California at Berkely, Los Angeles, and Santa Barbara
University of Connecticut
University of Illinois
University of Maryland
University of Massachusetts
University of Southern California
University of Texas at Austin
University of Waterloo
Yale University

Other Countries

Australian National University
Macquarie University
National University of Singapore
Technion
Tokyo University of Mercantile Marine
Tsinghua University
University of Newcastle
University of New South Wales

H. Visiting Scientists

This appendix gives a listing of scientists that have visited the department during 84–89. Only visits of a week or more are listed.

1984–1985

Mr Konrad Braun
Div of Automatic Control, ETH, Zürich, Switzerland
(Jan 15 – May 31 1985)

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

1985–1986

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

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

Dr Per-Olof Gutman
Electro Optical Ind.,
Rehovot, Israel
(June–July 1985 and 1986)

Dr David J. Hill
University of Newcastle,
Department of Electrical and Computer Engineering,
New South Wales, Australia
(1 Jan – 30 Dec, 1986)

Professor Richard Johnson, Jr.
Cornell University, Ithaca, NY, USA
(17 Sept – 21 Oct 1985).

Dr Wolfgang Kreutzer
University of Canterbury, Department of Computer Science,
Christchurch, New Zealand

(18 Nov, 1985 – 17 Jan 1986).

Professor John F. MacGregor
McMaster University, Hamilton, Canada
(Aug – Sept 1985)

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

1986–1987

Professor Rod Bell
Macquarie University,
School of Mathematics and Physics,
New South Wales, Australia
(May 5 – June 30 1987)

Dr Mike Denham
Kingston Polytechnic,
School of Electronic Eng. and Computer Science,
Kingston upon Thames, UK
(5 Nov – 5 Dec 1986)

Professor Dean Frederick
Rensselaer Polytechnic Institute,
Electrical Computer and Systems Engineering Dept.,
Troy, New York, USA
(18 May – 17 July 1987)

Professor Peter Gawthrop
University of Glasgow,
Department of Mechanical Engineering,
Glasgow, UK
(1 April – 31 July 1987)

Professor Kohei Ohtsu
Tokyo University of Mercantile Marine,
Department of Navigation,
Tokyo, Japan
(18 March – 18 Dec 1987)

1987–1988

Professor Rod Bell
Macquarie University, School of Mathematics and Physics,
New South Wales, Australia
(25 Jan – 9 Feb 1988)

Professor J. Douglas Birdwell
Department of Electrical and Computer Engineering,
The University of Tennessee, Knoxville, Tennessee, USA
(2 May – 30 June 1988)

Mr Stephen DeWeerth
Caltech, Pasadena, California, USA
(7 Sept – 2 Oct 1987 and 14–29 June 1988)

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

Professor Dean Frederick
Rensselaer Polytechnic Institute,
Electrical Computer and Systems Engineering Dept.,
Troy, New York, USA
(18 May – 17 July 1987)

Dr Per-Olof Gutman
Electro Optical Ind., Rehovot, Israel
(1–21 July 1987)

Professor C. C. Hang
National University of Singapore, Singapore
(1 Aug – 30 Oct 1987)

Dr David J. Hill
University of Newcastle,
Department of Electrical and Computer Engineering,
New South Wales, Australia
(11–29 Jan 1988)

Professor Robert Kosut
Integrated Systems Inc, Santa Clara, CA, USA
(3–18 Sept 1987)

Dr Wolfgang Kreutzer
University of Canterbury, Department of Computer Science,
Christchurch, New Zealand
(1 Dec 1987 – 26 Jan 1988)

Mr Stephen Murphy
Rensselaer Polytechnic Institute, Troy, New York, USA
(1 Sept 1987 – 19 Aug 1988)

1988–1989

Professor Carlos Canudas
Laboratoire d'Automatique de Grenoble
ENSIEG, Grenoble, France
(29 Aug – 19 Sept 1988)

Professor C. C. Hang
National University of Singapore, Singapore
(11–15 Oct 1988)

Mr Pablo Iglesias
University of Cambridge, Dept of Engineering
Cambridge, Massachusetts
(11 Jan – 21 April 1989)

Professor Robert Kosut
Integrated Systems Inc, Santa Clara, California
(28 April – 5 June 1989)

Professor Neville W. Rees
School of Electrical Engineering and Computer Science
University of New South Wales
Kensington, New South Wales, Australia
(9 Sept – 9 Dec 1988)

Professor Jean Jacques Slotine
Nonlinear Systems Laboratory, MIT
Cambridge, Massachusetts, USA
(22 Aug – 2 Sept 1988)

Mr Stéphane Sallé
Laboratoire d'Automatique de Grenoble
ENSIEG, Grenoble, France
(From 13 February 1989)

Professor André Tits
Dept of Electrical Engineering and Systems
Systems Research Center, University of Maryland
College Park, Maryland, USA
(5–30 Sept 1988)

Ms Claire Valentin
Laboratoire d'Automatique de Grenoble
ENSIEG, Grenoble, France
(31 March – 15 Sept 1989)

I. Longer Visits by Members of the Department 84–89

In this appendix is a listing of visits of members of the department during 84–89. Only visits of a month or more are listed. Apart from these longer visits many visits of 1–3 weeks have been made during the period.

1984–1985

Sven Erik Mattsson visited USA for five weeks in July to August 1984 together with Hilding Elmqvist. They visited Stanford University, Stanford Silicon Graphics Inc, Mountain View and Sun Microsystems Inc, Mountain View. Mattsson then then visited professor Polak's group, University of California, Berkeley, and worked with their CAD package DELIGHT.

Tomas Schönthal visited the USA during the spring 1985. He attended the CACSD'85 symposium in Santa Barbara, CA (March 13-15). The following six weeks he spent with Alan Laub's group at University of California, Santa Barbara, integrating their state-of-the-art numerical algorithms with our own design package Synpac. Finally he visited John Little at The MathWorks, Portola Valley, CA for three weeks, sharing their experiences in developing engineering software for personal computers.

1985–1986

Rolf Johansson spent six month with Laboratoire d'Automatique de Grenoble, France, during 1985. The visit was financed by Centre National de la Recherche Scientifique (CNRS) of France and Naturvetenskapliga Forskningsrådet (NFR) of Sweden.

Bengt Mårtensson spent one month in the USA during April and May 1986. He visited the following universities: Arizona State University, Dept of Electrical and Computer Engineering and Dept of Mathematics; University of California, Berkeley, Department of Electrical Engineering; University of Maryland, College park, Department of Electrical Engineering and the Systems Research Center; Harvard University and Massachusetts Institute of Technology.

Lars Nielsen spent the year 1985–86 as a visiting researcher at Caltech, Pasadena, USA. He was working with professor Carver Mead and his group at the Department of Computer Science.

1986–87

Karl Johan Åström In the middle of September 1986 he went to USA where he spent five weeks. He participated in IEEE Workshop on the Challenge to Control, held in Santa Clara, California, where he made a keynote talk. He participated in IEEE Third Symposium on Computer-Aided Control System Design (CACSD), 24–26 Sept, Arlington, Virginia, and presented two papers. During his stay he visited Pentagon to listen to presentation of AI activities in the US army, and he visited DuPont in Delaware to discuss advanced process control. He also visited several companies and universities in California: Advanced Decision Systems, HP Research, UC Berkeley, UC Santa Cruz, Reasoning Systems, Integrated Systems, Apple, IBM, Systems Control.

Björn Wittenmark was on sabbatical leave during the academic year 1986–1987. He spent the year at Department of Electrical and Computer Engineering, University of Newcastle, Australia. During the visit in Australia he made research in the area of adaptive control together with G.C. Goodwin, R.J. Evans and R.H. Middleton.
On the way to Australia he lectured and visited in China for three weeks at the following places: Tsinghua University, Beijing, East China Normal University, Shanghai, and Shanghai University of Science and Technology. In July he spent two weeks at Department of Chemical and Nuclear Engineering, University of California, Santa Barbara.

1987–88

Karl Johan Åström In September–October he went to USA, where he participated in the "13th Annual Advanced Control Conference" at Purdue University. He also visited the Center for Intelligent Systems at MIT, Cambridge, and the University of Texas at Austin.
During May–June 1988 he was visiting fellow at Oxford University, UK.

1988–89

Magnus Akke From Mars to August 1989 he visited University of Newcastle, Australia.

Bo Bernhardsson visited INRIA in Paris September 5 – October 14, 1988. During that period he also visited Professors Praly and Levine at Ecole des Mines, Carlos Canudas, ENSIEG Grenoble, Mme Siguerdidjane at SUPELEC, Paris.

Lars Nielsen During May he participated in the "IEEE Int. Conference on Robotics and Automation" in Scottsdale, Arizona, May 14–19, and he made a number of visits the weeks before. The major ones were; MIT, Harvard University, Rensselaer Polytechnic Institute, University of Maryland, University of California, Berkeley, Caltech.