VINNOVA's Competence Center **ISIS**
Information **S**ystems for **I**ndustrial Control and **S**upervision
Report for Phase 3: Jan 2001 to Dec 2003

May 10, 2004

1 Executive Summary

ISIS is center of ten industrial partners and six research laboratories, focusing on industrial control and supervision problems, bridging techniques from computer science and control engineering.

The most important challenges of a competence center are to maintain the right balance between scientific production and industrial relevance, to produce well trained graduates, and to have an active interchange of personnel.

We believe that ISIS has handled these challenges in a successful manner. Publications in well-reputed international journals and conferences and a healthy productions of graduates (MSc, TechLic, and PhD.) has been combined with intense interaction with our industrial partners. Several successful commercial products have their origins in ISIS projects and the companies witness about the ISIS impact on their R&D activities. The flow of people between the ISIS research groups and the ISIS companies has been substantial.

The creation of ISIS has lead to a number of benefits for the partners. The close industrial/university cooperation has, for example, meant patents in research groups that never filed a patent application before ISIS. Advanced signal processing applications in industrial products would not have been implemented without the collaboration with ISIS university laboratories. ISIS has been a valuable recruitment platform for the companies. Also, ISIS has spurred an interest for the engineers in the companies to join the research groups as PhD students.

The fact that several international partners have contacted the ISIS groups for formulating projects for the EU 6th framework program within the ISIS area can be seen as an evidence that our work has attracted international interest.

In this report we shall give a number of facts that describe the organization, projects, and production of ISIS during Phase 3 (Jan 2001 – Dec 2003). Hopefully, it will also convey a major message, that ISIS has meant an important and useful vitalisation of the way to cooperate between industry and university, across research specialties.

The remainder of this report is organized as follows

2 Summary of Key Numbers for Phase 3 and Since the Start of ISIS

Summary of Key Numbers for Phase 3: 2001 - 2003

- 2 graduated PhD's
- 10 graduated TechLic
- 67 master theses
- 18 articles, published in refereed international journal
- 8 patents
- 99 international conference publications
- 32 technical reports

Summary of Key Numbers for Phase 2: 1998 - 2000

- 9 graduated PhD's
- 5 graduated TechLic
- 47 master theses
- 11 articles, published in refereed international journals
- 57 international conference publications
- 27 technical reports

Summary of Key Numbers for Phase 1: 1996 - 1997

- 4 TechLic
  In addition, one licentiate thesis and two PhD theses have been completed, partly within ISIS.
- 19 international conference publications
- 7 technical reports

3 Some Success Stories

Before embarking on the formal list of projects, papers and patents, let us highlight some results from the last few years of ISIS activities - *achievements that would not have been obtained without the special research environment that is created by the competence center concept.*

Iterative Learning Control for Industrial Robots

Based on the ABB Robotics interest to improve the robot accuracy a factor of 10 from 1 mm to 0.1 mm, an ISIS project to investigate the Iterative Learning Control (ILC) techniques was formulated in 1996. As a PhD student, Mikael Norrlöf spent about 25% of his time at ABB during the first year of the project to learn the application, the robot product requirements and the robot controller software. At the same time he also set up a robot lab in Linköping, where he developed an ILC interface to the ABB controller to be able to manipulate the robot with ILC control. New ideas and algorithms were developed through theoretical studies, simulations and experiments and

the concept coming out from this research showed such promise that ABB took the risk in 1999 to apply the technique in their robot controller directly in a big critical customer project. In August 2000, 30 robots with ILC both for parameter tuning and servo error tuning were delivered to Tower Automotive in the US. The robot application of ILC was patented and thanks to the outstanding robot performance with ILC, ABB got an extra sales volume of more than 700 robots in the time period 2000 - 2002.

The project was presented in 2001, at ABB's annual "Technology Event" in Zürich as one of the great break throughs within the company during that year. Moreover it was one of three finalists for Ny Teknik's Technology Award "Guldmusen" in 2001. VINNOVA has used this project as a "flagship example" of what competence centres can achieve ("Competence Centres pay off" in *Research and Innovation for sustainable growth*, VINNOVA Information VI 2002:1)

The project has been successful both from the commercial aspect just described, but also scientifically, in that Mikael Norrlöf has published many articles about theoretical and algorithmic aspects of ILC. He has become well established in the international research community of the area, and has been frequently invited to participate in conferences, workshops, and international tutorials.

From Terrain Navigation to Particle Filters to Gripen Test Flights and to Other Industrial Products

Based on Saab Bofors Dynamics' leading competence and long experience in navigation, especially terrain navigation systems, together with Saab Aerospace's knowledge of aircraft applications, the ISIS navigation project was formed around sensor fusion and integrity monitoring. The project started in 1996 with a number of master theses and Jan Palmqvist and Niclas Bergman as PhD students.

The ideas turned out to be very powerful in terms of both theory and industrial applications. A prolific collection of applied projects and theoretical results has grown from this seed.

Niclas Bergman started to work on the problem of merging terrain map (altitude) information with conventional navigation data. This was formulated as a Bayesian estimation problem over fixed, and later adaptive, space grids. A prototype algorithm was successfully tested on real data around the time of the previous ISIS evaluation. As a result of Bergman's work and a number of Master theses, Saab Bofors Dynamics modified the estimation algorithm in their existing terrain navigation systems TERNAV.

About the same time, Jan Palmqvist (then sharing his time between the University and SAAB Aerospace) finished an ISIS funded licentiate theses on integrity monitoring of integrated navigation system. This was followed up in a another ISIS licentiate thesis by Per-Johan Nordlund on particle filters in navigation systems. Palmqvist and Nordlund returned to Saab Aerospace as managers for the navigation group after finishing their lic degrees. In a joint integration project between Saab Bofors Dynamics and Saab Aerospace, all of the above came together in new integrated systems for navigation and landing for the GRIPEN aircraft (NINS and NILS). These systems have now been successfully test-flown in GRIPEN and will be delivered to the Swedish Air Force in the near future

Also about the same time, the links between Bergman's approach and the emerging Particle Filter techniques become clear. Thus, ISIS researchers had a head start on Sensor Fusion techniques based on particle filter, and got a visible position in the international research on this topic, manifested e.g. in the survey paper "Particle Filter for Navigation, Positioning and Tracking" (IEEE Trans. Signal Processing, vol 50(2), pp 425-437, 2002). They also receive regular invitations to International Conferences.

With ISIS' wide application contacts, the ideas and algorithms turned out to be applicable to a number of problems. For example, the ISIS partner NIRA developed a map-based tool for car navigation: MAP-aided positioning. This is now available as a software product. Moreover, the ideas found use in several applications for Saab Bofors Dynamics on target tracking and with Volvo (outside ISIS) on car collision avoidance.

4 Basic Facts

ISIS started in October 1995 as a coalition between 7 companies and 5 research groups at Linköping University focusing on control and supervision problems. Since then one company left and four more joined ISIS. Also, there has been some changes in the research groups in the center. In this section, *Basic Facts*, administrative information about ISIS will be given. The partners will be listed and we also give a summary of economic facts, budget and result for 2002. A snapshot of people working within ISIS (for the year 2002) is available in Appendix A.

4.1 Partners

As of January 1, 2003, the partners of ISIS were as follows.

From Industry

- ABB Automation Technologies, Process Automation, 721 59 Västerås
- ABB Industry Solutions, 721 67 Västerås
- ABB Corporate Research, 721 78 Västerås
- ABB Robotics AB, 721 68 Västerås
- Ericsson AB, Box 1885, 581 17 Linköping
- Mecel AB, Box 73, 662 22 Åmål
- NIRA Dynamics AB, Teknikringen 6, 583 30 Linköping
- Saab AB, 581 88 Linköping
- Saab Automobile AB, Box 636, 151 27 Södertälje
- Saab Bofors Dynamics AB, 581 88 Linköping

From University

- Division of Automatic Control, Department of Electrical Engineering
- Division of Communication Systems, Department of Electrical Engineering
- Division of Vehicular Systems, Department of Electrical Engineering
- Theoretical Computer Science Laboratory, Department of Computer and Information Science
- The Embedded Systems Laboratory, Department of Computer and Information Science
- The Real-Time Systems Laboratory, Department of Computer and Information Science

4.2 Personnel

During the years a large number of people have been involved in the ISIS projects. A snapshot of the personnel situation is given in the table in Appendix A. It lists 71 people in industry and university that have been active in ISIS during 2003, along with the number of man-months spent on ISIS projects.

The management structure is such that the *Director*, Lennart Ljung, with the aid of the *ISIS Secretary*, Ulla Salaneck, handles the day-to-day issues and prepares the Board meetings.

The *ISIS board* decides the strategy, the budget, and new projects. It also monitors the progress of the projects. The board meets 3-4 times a year.

The *ISIS Reference Group* meets once a month. It plans seminars, workshops and supervises the projects. It also prepares proposals for new projects. The members of the Reference Group are invited to participate in the Board meetings as observers.

The members of these groups are as follows.

Board Members

Torgny Brogårdh	ABB Robotics, chairman
Ulf Moberg	ABB Automation Technologies, Process Automation
Urban Forssell	NIRA Dynamics AB
Joakim Ed	Saab Automobile AB
Ulf Persson	ABB Industry Solutions
Per Erik Modén	ABB Corporate Research
Anders Göras	Mecel AB
Jan Palmqvist	Saab AB
Göran Johansson/Anders Skeppstedt	Saab Bofors Dynamics AB
Gunnar Bark	Ericsson AB

Reference Group

Petru Eles	Linköping University
Lars Eriksson	Linköping University
Torkel Glad	Linköping University
Svante Gunnarsson	Linköping University
Fredrik Gustafsson	Linköping University
Jörgen Hansson	Linköping University
Inger Klein	Linköping University
Lars Nielsen	Linköping University
Ulf Nilsson	Linköping University
Erik Sandewall	Linköping University
Karl Einar Sjödin	VINNOVA

5 Performance and Development as a Competence Center

In this section the strategy and operation of ISIS are described. The vision of the center is outlined, as well as progress and problems on the road to the goals. Moreover, the international, national, and university contacts of ISIS are mentioned. The impact of ISIS on these external surroundings is commented upon.

5.1 The ISIS Strategy Statement

The following statement about the goals of ISIS was adopted in February 2001.

The overall strategy for ISIS is to be the Swedish center of competence for the design of industrial systems for control and supervision. This means that the center must work with technology for control and supervision, critical for the future product development in Swedish industry. In order to guarantee that the competence developed is critical for the industry, the activity of the center is based on collaboration projects with the participating companies. Therefore the selection of projects is very important and of highest priority in this respect is to select projects which develop competence of big impact on the industrial partner. Simultaneously, the center must put a high priority on the scientific quality of the projects and on the competence handling. The competence developed must be both transferred to the industrial partners and retained and further developed in the center.

The projects *In order to continuously increase the competitiveness of the center, the projects must be chosen in such a way that the center remains an interesting partner for the industry in the most important areas of control and supervision of industrial systems.*

A mix of projects of different characters is desired:

- **Enhancement projects** *which aim to improve the functioning of existing and new industrial products*
- **Breakthrough projects** *which aim at developing and testing the use of new techniques in the industrial partners' products and design processes.*
- **Competence development projects** *which aim at developing general competence that is essential for the general activity area of ISIS.*

Focus areas *The focus areas of the ISIS project are the following three:*

- *Projects that secure areas of basic competence, such as system identification and modeling, model based control and real-time aspects of control and supervision.*
- *Model based detection and diagnosis*
- *Sensor fusion techniques*

How to strengthen the focus areas and make them visible? *It is necessary to run a collection of projects in the areas of sensor fusion and detection/diagnosis that of critical mass both in volume and scope. Mutual interactions between the projects will help focusing on essential basic problems.*

It is natural to seek further partners in the sensor fusion area also outside ISIS. Furthermore, it is desirable to arrange biannual conferences on sensor fusion and on diagnosis and detection in addition to the yearly workshops. Collecting information from the different projects in state of the art articles are other desired activities.

5.2 Progress

We believe that we have been successful in our work towards the goals outlined in the strategy document. The production of graduate exams and scientific publications in internationally reputed journals and conferences has been satisfactory, as is further detailed in Section 6. At the same time, the companies have appreciated ISIS's contribution to new products, product enhancements and long-range R&D activities, as manifested in the company statements in Section 7. The crucial balance between industrial involvement and scientific quality has been kept in a way that we are proud of.

An important sign of the companies' appreciation of ISIS is the willingness to let their engineers enter as part-time graduate students as well as employing our graduates. See Section 7.3.

While keeping a fairly broad competence profile, we have still been able to focus on sensor fusion and diagnosis. Thirteen ISIS theses directly deal with these issues.

5.3 External Collaboration

ISIS has an International Scientific Advisory Board, consisting of the following persons

- Prof. J. S. Baras, University of Maryland, USA
- Prof. A. Benveniste, IRISA, Rennes, France
- Prof. E. M. Clarke, Carnegie-Mellon University, USA
- Prof. B. Neumann, Universtität Hamburg
- Prof. E. Sandewall, LiTH.

This advisory board forms a kernel for international contacts and scientific feedback.

In addition, each of the research groups has an extensive international contact network. The groups have joint projects with many laboratories and researchers around the world and active Post Doc programs in both directions. It would lead too far to list all those contacts here.

5.4 Internal Collaboration

The internal collaboration between the groups and between industry and university takes place in the joint projects, and in joint seminars and workshops. We have also organized special, so called TKG-groups (Technology Contact Groups) which are groups formed by a number of university researchers and company engineers. There are several TKG groups, reflecting special interest for the different ISIS companies. The meetings of the TKG-groups, which are on the average four times per year, give important cross disciplinary insights. The general technical discussions carried out there serve both the purpose of giving a deeper understanding of the technical problems and applications in the company, and seeding ideas for new projects. Some of the TKG-meetings are devoted to "micro-courses" on, e.g. wavelet theory or state of the art of real-time data bases.

While the concept of ISIS as work unit is essential, it is also very important that the researchers have a clear "home" in their groups. The scientific competence thrives also from other, and perhaps more theoretically oriented, activities in the research groups. The ability for the research groups to cover a spectrum from sophisticated theory to industrial problems is instrumental for a good balance between "theory and practice" in engineering. ISIS plays a vital role for this and also benefits from being close to the other research activities in the groups.

5.5 The Center and the Host University

There may be a potential conflict between a Competence Center's goal and those of the Department/Faculty/University.

We are happy to note, though, that ISIS has encountered no such problems whatsoever. We have the best relations with the university leadership at all levels. We note also, e.g., from the Annual reports, that the University is proud of our achievements. ISIS receives a yearly cash contribution of 1000 KSEK from the University, which is used to fund research associates.

The good relationships are also confirmed by the most beneficial interaction at the different education levels. See Section 6.5 for further information about this.

6 Technical Results and Scientific Output

This section deals with the technical program of ISIS, and the production of scientific publications and academic exams. The output in terms of products and product enhancements will be described in Section 7.

6.1 Research Program

The research program is divided into five main areas, that have been unchanged since the start of ISIS. Within each of the areas, several projects are carried out. The projects have varied over the years. The main areas as well as a snapshot of the projects, for the year 2003 is as follows:

Data Bases for Control, Modeling and Simulation

1 Embedded Real-time Data Bases for Engine Control

Diagnosis, Supervision and Safety

2 Diagnosis and Supervision of Vehicle Functions

3 Fault Isolation in Object Oriented Control Systems

4 Detection and Diagnosis in Control Systems

Techniques for Developing Integrated Control and Information Systems

5 Design Environment for Real-Time Embedded Systems in Control-Related Applications

6 Resource management in Wireless Communication Systems

Methods for Synthesis of Control and Supervision Functions

7 Supervision and Control of Industrial Robots

8 Nonlinear Model Predictive Control

Signal Processing in Integrated Control and Supervision Systems

9 Navigation Systems

10 Signal Interpretation and Control in Combustion Engines

11 Sensor Fusion

This list of projects, as well as the resources alloted to them follows the general plan for Phase 3.

6.2 Technical and Scientific Achievements

The space limitation for this report does not allow a detailed description of the progress within the individual projects. That can be studied on our web page (`http://www.control.isy.liu.se/isis/`). Also, the annual report for 2002 (Enclosure III) contains project summaries for that year.

The bottom line of the achievements are the international publications and graduate exams, as described below, and our industrial partners' satisfaction, as evidenced in Section 7.

6.3 Scientific Papers

A list of publications in scientific journals and conferences is given in Enclosure I. This list only contains publications with an ISIS graduate student or an ISIS research associate as an (co)author, and does not cover other publications by ISIS supervisors.

In addition, several PhD, TechLic, and MSc theses have been completed as described in the next section.

6.4 Examination

All ISIS projects involve at least one graduate student. Graduate studies can be completed as a TechLic exam (which is about 50% of a PhD exam.) or as a PhD degree. In addition, more than 100 MSc theses have been prepared within or in close cooperation with ISIS project. In this section we list the PhD and TechLic degrees that have been completed within ISIS. For the MSc exams we refer to Enclosure I. Moreover, see Section 7.4 for a description of how MSc theses have been used in a systematic way to build up competence and a simulation platform at ISIS companies.

PhD-degrees 2000 - 2003:

- Mikael Norrlöf. *Iterative learning control: Analysis, design and experiments*, 2000. Mikael Norrlöf is employed as research associate at Linköping University.
- Henrik André Jönsson. *Indexing time series data*, 2002. Henrik André Jönsson is employed at Xelin Research & Development AB.
- Johan Löfberg. *Minimax Approaches to Robust Model Predictive Control*, 2003. Johan Löfberg is currently employed as a postdoc at ETH, Zürich, Switzerland.

PhD-degrees 1997 - 1999:

- M. Ronström. *Design and modelling of a Parallel data Server for Telecom Applications*. 1998. Ronström is employed by Ericsson AB.
- Niclas Bergman. *Recursive Bayesian Estimation: Navigation and Tracking Applications*. May 1999. Niclas Bergman is employed by Saab Tech Systems.
- Lars Eriksson. *Spark Advance Modeling and Control*, May 1999. Lars Eriksson is employed as lecturer at Linköping University.
- Mattias Nyberg. *Model Based Fault Diagnosis: Methods, Theory and Automotive Engine Applications*. June 1999. Mattias Nyberg is employed by Scania AB.
- Magnus Larsson. *Behavioral and Structural Model Based Approaches to Discrete Diagnosis*. December 1999. Magnus Larsson is employed by ABB Robotics.
- Lin Ling. *The IP Index*. March 1999. Lin Ling is employed by Ericsson AB.
- Martin Sköld. *Active data base management systems for monitoring and control*. 1997. Martin Sköld is employed by Ericsson AB.

Licentiate degrees 2000 - 2003:

- Dan Lawesson. Towards behavioral model fault isolation for object oriented control systems. 2000.
- Johan Löfberg. Linear model predictive control: Stability and robustness. 2001.
- Rickard Karlsson. Simulation based methods for target tracking. 2002.
- Per-Johan Nordlund. Sequential Monte Carlo filters and integrated navigation. 2002.
- Måns Östring. Identification, diagnosis, and control of a flexible robot arm. 2002.
- Niclas Persson. Event based sampling with application to spectral estimation. 2002.
- Per Andersson. Intake air dynamics on a turbocharged SI-engine with Wastegate. 2002.

- Trian Pop. Scheduling and opimization of heterogeneous time/event-triggered distributed embedded systems. 2003.
- Mattias Krysander. Design and analysis of diagnostic systems utilizing structural methods. 2003.
- Erik Geijer Lundin. Uplink load in CDMA cellular systems. 2003.

Licentiate degrees 1997 - 1999:

- Niclas Bergman. Bayesian Inference in Terrain Navigation, 1997.
- Lin Ling. A Value-based Indexing Technique for Time Sequences, 1997.
- Jan Palmqvist. On Integrity Monitoring of Integrated Navigation Systems. 1997.
- Mattias Nyberg. Model Based Diagnosis with Application to Automotive Engines. 1997.
- Mikael Norrlöf. On analysis and implementation of iterative learning control, October 1998.
- T. Padron-McCarthy. Performance-polymorphic declarative queries, 1998.
- Tim Heyer. COMPASS;Introduction of Formal Methods in Code Development and Inspection. 1998.
- Henrik André-Jönsson. Indexing time-series data using text indexing methods, 1999.
- M. Sköld. Active Data Base Management Systems for Monitoring and Control.
- Lars Eriksson. Closed-loop Spark-advance Control using the Spark Plug as Ion Probe, 1997.

6.5 Education and Training Activities

A graduate school ECSEL ("Excellence Center for Computer Science and Systems Engineering in Linköping") has been established to provide a broader curriculum for PhD students IT-related areas. The goal is the educate people with a broad and integrated view across software, hardware and "systemware". The founders of ISIS have also been among the initiators of this graduate school. Most ISIS graduate students are enrolled in ECSEL. This means that the competence and research goals of ISIS match the ECSEL course program in an excellent manner. The first phase of ECSEL was completed in 2002, and a second 3-year phase started in 2003, funded by the Foundation for Strategic Research (SSF).

In the undergraduate School of Engineering at Linköping University, special study programs ("profiles") have been established within the Electrical Engineering and Computer Engineering programs. These profiles are called "Control and Information Systems", and the Director of ISIS is responsible for their curricula. They have turned out to be quite popular among the undergraduate students. This demonstrates the impact of ISIS also on undergraduate education.

In addition to the undergraduate and graduate programs, ISIS also offers workshops, seminars, mini-courses to the industrial partners.

7 Industrial Relevance, Benefits and Effects

This section deals with the industrial benefits of the ISIS activities. This is done primarily by directly quoting statements by the industrial partners on what concrete benefits they have experienced in ISIS.

7.1 Company Statements: Industrial Relevance of the ISIS Projects

ABB Robotics

"ISIS develops competence in the following areas together with ABB Robotics:

- Iterative Learning Control (ILC)
- System Identification for complex robot dynamics
- Model-based fault isolation in object oriented software
- Diagnosis of mechanical and electrical robot components
- Servo reference optimization
- Servo loops optimization

This competences development has so far resulted in the following industrial results:

1. ILC (Iterative Learning Control) was introduced in the ABB Robot Controller S4C+ in 2000, used especially for laser cutting by the automotive industry and their sub suppliers. This functionality has given an added sales of about 650 robots for ABB during 2000 - 2002. One version of ILC has also been used to obtain an accurate force direction for robots pressing components against car frames while other robots fasten the components by means of arc welding. 80 robots have been sold with this functionality up to 2002. Presently, ILC is tested for grinding and milling applications and a grinding station with ILC has been installed for turbine blade grinding at GE in US.
2. The system identification competence has been applied as one component in an automatic robot servo tuning tool that is used at ABB Robotics to decrease the time and increase the quality of the tuning of the model-based robot servo.
3. The system identification competence has also been important for the development of a high performance load identification functionality, which is a standard in the ABB controllers since 1998.
4. The fault isolation development has resulted in a tool (Dr Robot) for automatic isolation of the root cause problem from a list of error reports generated by the object oriented ABB Robot Controller software. The plan is to introduce this in 2004 as a tool in the ABB robot customer support tool box.
5. The diagnosis of robot components that influence the dynamics of the robot has been studied in a licentiate work. It was shown that system identification and residual calculations will be possible to use to diagnose upcoming problems with the motors, gear boxes, transmissions and loads. Today a very simple diagnosis system is available in the ABB controller and with this as a base more advanced model-based diagnosis is expected to become a product in 2005.
6. The servo reference optimization project started in 2002 and relies on a new concept for the optimization of trajectory dynamics. The optimization of trajectory speed, acceleration and acceleration derivative is made in robot joint coordinates and is made without the need to have any knowledge of the trajectory geometry in the task space or of the robot kinematics. This makes efficient software implementation and modularization possible for the geometric trajectory interpolation, the

dynamic optimization, the kinematic model calculations and the dynamic model calculations. Moreover, most of the motion control functionality will get higher performance, for example, the time needed to run a complicated trajectory with a robot may decrease 10 - 30% and the mechanical stress on the robot components may decrease with up to 40% . This project is expected to be the next ABB Robotics break through project in the ISIS collaboration. Product development is expected to start in 2005.

7. The servo optimization relies on LQG techniques. It has been shown during the collaboration that both the robot stiffness and the robustness of the model-based control can be increased drastically by applying LQG when arm sensors are introduced in the control loops. Thus, the robot stiffness can be increased a factor of 5 - 10, which means that industrial robots can be used for a wide spectrum of material removal applications, for which robots are too compliant today. This is expected to become a very important break through in robotics. However, product development will probably not be possible to start until 2006 - 2007 because of the necessity to make changes in the mechanical robot design before arm sensors can be introduced."

SAAB Aerospace

"A number of applications have their roots in the research performed within ISIS. One example is the terrain reference navigation system, a central part of the new autonomous landing system for Gripen, where the point mass filter developed by Niclas Bergman (Project 11) is used to reduce the lock on time for the system – a crucial parameter in a landing application.

Another example is the integrity monitoring of the navigation system (Project 9), which provides information to the landing system, that is being developed using ideas and information brought forward during research and discussions within ISIS."

SAAB Bofors Dynamics

"The work on Bayesian filtering (Projects 9 and 11) have been directly useful in our products, especially some of the Terrain navigation systems. The manifold filters in combination with Bayesian statistics will also be a powerful tool to evaluate approximations in sensor-fusion and adaptive filtering among a number of products. The theory that has been developed in this projects has also increased the knowledge level for our employees so they can understand and use more advanced theory in later projects and products."

SAAB Automobile

"The project at Vehicular Systems on model based diagnosis and detection of very small air leakages was instrumental for us when we decided on the route for future development of functionality: The approach and the use of models is now a natural method that we use for development of new algorithms in our engine control system (Trionic) both for diagnosis and control.

The basic modeling specifically directed towards turbo engines and the utilization of these models in function development are directly coupled to our own development process towards future advanced control systems. This includes for example directed projects on driveline resonances and joint projects on implementation of experimental platforms."

**ABB Automation Technologies, Process Automation,
ABB Industry Solutions and ABB Corporate Research**

"These three units have focus on process control and have coordinated their ISIS activities and projects.

One specific result of the ISIS cooperation is the Master Thesis "Pre-Specification of Zero Transfer Functions in Identification of Multi-Variable Systems" by Anders Fröberg. The result of the thesis has been included in the multi-variable Model Predictive Controller "OptimizeIT Predict & Control" from ABB. It addresses a common objection to the use of state-space models in Model Predictive Control: that prior knowledge about non-existent dependencies between inputs and outputs has been hard to use when identifying a multivariable process. The project on model predictive control for non-linear processes that has resulted in Johan Löfberg's Ph D thesis "Minimax Approaches to Robust Model Predictive Control" has contributed to our general knowledge build-up that will be exploited in further product enhancements.

ABB has developed a rather general tool to detect and isolate faults in the process industry. This tool now runs on two pulp & paper mills. Some of the important basic ideas and solutions to problems for the tool can be attributed to ISIS.

Over the years we have had a number of discussions, with mutual exchange of information, on the identification of process models. The discussions cover lower order black-box models for controller tuning, suitable for a loop-tuning tool, as well as estimation of parameters in physical models. To have direct access to the world-renowned expertise from Linköping in this area is extremely valuable. This and the knowledge gained through the ISIS activities on diagnosis contribute in our continuous development of tools for assessment and improvement of control loop behavior."

Mecel AB

"From Mecel's perspective the co-operation with ISIS plays an important role for our ability to build relevant competence within our core-business, i.e., ion-sense based diagnosis and engine control. We work with cutting edge technology in this area. Our customers turn to us in order to benefit from our know-how and the applications we work on are demanding. An example of our customers is Ferrari Sportiva, the formula one racing team. We are proud to inform the reader that in March 2003 it was announced that Mecel has become an official partner to Ferrari.

Within the competence center, we have primarily co-operated with the division of Vehicular Systems at Linköping university. The dialogue and exchange of information and competence between Mecel and Vehicular Systems in form of mutual projects play an important role. The contact with Prof. Lars Nielsen and Lars Eriksson, has been result oriented and much appreciated. Specifically, we have together applied for and received a patent in the area of model based signal processing applied to ion sense signals. The patent has been used in a project for a paying customer.

Other examples of application areas of interest for Mecel that are studied within ISIS, to mention a few, are model based diagnosis, detection, combustion engine modelling and control, and non-linear signal processing.

Mecel values the co-operation with ISIS highly."

Ericsson AB

"Ericsson Research works mainly in core telecommunications research, applied research supporting the product and business organizations, and standardization. The ISIS cooperation touches base with all three areas to some extent.

The work on algorithms and modeling for power control has resulted in several patented methods, currently considered for possible use in Ericsson radio system products. As seen in field trials with commercially deployed networks, the developed models provide relevant descriptions of certain dynamical power control behavior.

When launching a multitude of services in the 3G wireless networks, the uplink load situation becomes more complicated to analyze. This will be very important if the systems become limited by the uplink capacity. The work on uplink load estimation is discussed with the product organization for future releases and with standardization to facilitate an efficient signaling of information in the network."

NIRA Dynamics AB

"NIRA Dynamics currently has the following products that trace back to core ISIS competence areas:

- MAP (Map-Aided Positioning). The system is based on the particle filter and uses a digital street map and wheel speeds as the main sensor signals. The principle is the same as the terrain navigation system ISIS developed for SAAB. It also applies the sensor fusion concept in that additional sensor signals as gyroscope and GPS position are easily added to the product whenever available.
- TPI (Tire Pressure Indicator) is based on multi-level sensor fusion where sensor signals are fused into different model-based filters, and the outputs of these filters are in turn fused to a very robust and high-performance tire pressure estimator.

These products are also closely linked to the diagnosis project, since incorrect sensor information must be quickly detected and compensated for."

7.2 Forms for the Industrial Involvement

The industrial partners of ISIS participate in the activities in several ways:

- In the strategic planning by the board. Each company has also produced a statement about their strategic goals for participating in ISIS.
- Directly in ISIS projects as listed in Section 5.1.
- In technical discussions, outside the projects, in so called TKG-groups (Technology Contact groups).
- In seminars, workshops, mini-courses, arranged by ISIS.
- The flow of people in both directions between industry and academia is of course also a most important form of involvement.

7.3 Flow of People between Industry and University

The flow of people between the university and the ISIS companies – *in both directions* – is an integral part of the center's role. We point to the following examples of this exchange:

From Industry to University (and back)

- *Jan Palmqvist* worked about 10 years at SAAB Aerospace after receiving his Civ.ing. (MSc) exam. He then became "industridoktorand" (Industrial PhD student) sharing his time 50/50 between SAAB and the university. He became the project leader of the ISIS navigation project, received his TechLic degree in 1997, and then became the head of the SAAB Navigation Group.

- *Per Johan Nordlund* had worked 3 years at SAAB Aerospace and then joined ISIS as an ISIS funded Industrial PhD student, spending 60 % of his time on the Sensor Fusion project. After finishing his TechLic in 2002 he returned to Saab as a manager in the Navigation Group.
- *Rickard Karlsson* had worked 3 years at SAAB Bofors Dynamics, and was then an ISIS funded Industrial PhD student, spending 60 % of his time on the Sensor Fusion project. After finishing his TechLic he is now a full time PhD student, on leave from Saab Bofors Dynamics.
- *Niclas Persson* worked at NIRA Dynamics and became an industrial PhD student within ISIS in 2000 partly funded by ISIS. After finishing his TechLic in 2002 he returned to work full time at NIRA Dynamics.
- *Ingemar Andersson* has worked at Mecel for 2 years, and was an Industrial PhD student in the Vehicular Systems group. He was not funded by ISIS, but closely connected with the ISIS projects. He completed his TechLic in 2002, and is now employed by Mecel.
- *Per Andersson* worked 2 years at SAAB Training Systems, and then became a PhD student at the Vehicular System group, funded by ISIS for the project Signal Interpretation and Control in Combustion Engines. He completed his TechLic in 2002.
- *Mikael Ronström* has worked at Ericsson Utveckling AB throughout his doctoral studies at Linköping University. He finished his PhD thesis on Telecommunication data bases in 1998. He spent one day a week during 1999 as a researcher in the Laboratory for Engineering Data Bases at Linköping, funded by ISIS.

From University to ISIS Companies

- *Niclas Bergman* started to work at SaabTech Systems after his PhD, and he is currently responsible for sensor data fusion activities within all SAAB companies, which indicates the impact ISIS has on the sensor fusion area.
- *Fredrik Gunnarsson* worked partly on Ericsson premises during the initial phase of the ISIS project connected to Ericsson. To further strengthen the cooperation, he joined Ericsson at 80 %, while remaining 20% at the university co-supervising PhD students within ISIS.
- *Magnus Larsson* finished his PhD thesis in December 1999, within the project Fault Isolation In Object Oriented Control Systems, in close cooperation with ABB Robotics. Since April 1, 2000 he works at ABB Robotics.
- *Urban Forssell* finished his PhD in March 1999 and joined Mecel as responsible for the Control Group. The ISIS links between Mecel and the university were instrumental for this decision, even though he did not work with any ISIS project as a student. After one year at Mecel Urban Forssell became President of NIRA Dynamics AB and he is now representing NIRA Dynamics at ISIS Board of Directors.
- *Håkan Fortell* defended his PhD thesis in December 1995, and joined ABB Robotics shortly after that. Although he did not work within ISIS as a PhD student, the ISIS contacts were important for his, and ABB Robotics, choice.
- *Predrag Pucar* finished his PhD in 1995 and then joined Saab AB. Although he did not work within ISIS as a PhD student, the ISIS contacts were important for his, and Saab's, choice. He has been actively involved in ISIS activities.
- *Martin Sköld* finished his PhD in 1997, and managed the Telecommunication data base project during 1998. He now works with data base problems at Ericsson Utveckling AB.
- *Lin Ling* finished her PhD in 1999. She is now employed by Ericsson AB.

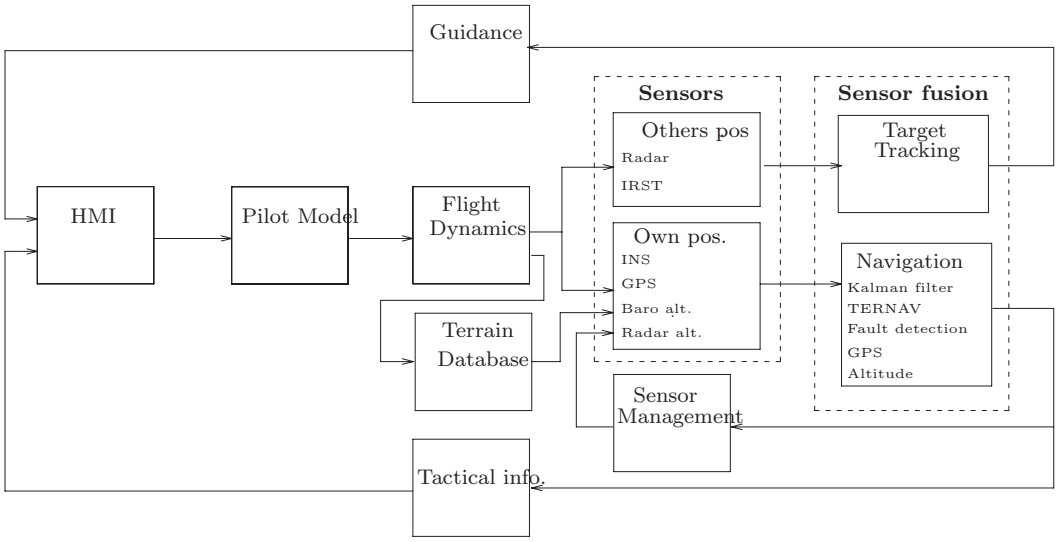

Figure 1: Block diagram for the connection the about 65 Master Theses that relate to the ISIS navigation and sensor fusion projects. The actual theses are listed in Enclosure I.

7.4 Strategic Use of Master Theses: An Example of Long Term cooperation within ISIS

Navigation and Sensor Fusion

Master theses play an important role in the cooperation between industry and university. Within ISIS we have tried to use this resource in a thoughtful way to strengthen both contacts and infrastructure within ISIS and the participating companies. This is particularly clear for a long series of master theses carried out at SAAB, building up a simulation platform for navigation and sensor fusion.

The planning of a simulation environment for navigation purposes was started in 1997, mainly by Jan Palmqvist then as an industrial PhD student from SAAB. Existing simulators at SAAB are either focused on aircraft dynamics (for control design purposes) or animation/visualization (for pilot training purposes). The vision was a simulator with realistic models of the sensors, where different parts of the navigation system can be evaluated. In this project, about 20 master theses have been performed at SAAB. Perhaps inspired by this effort, other companies have increased their number of master projects in this area significantly, and today around 65 theses have been completed in the aircraft navigation loop as illustrated in the block diagram in Figure 1. The navigation loop also includes target tracking of other aircraft.

The quality of the master theses are reflected in a number of awards and employments:

- The Polhem prize 1997 for best master thesis in Sweden.

- Radionavigationsnämnden first and second biennial award for best master thesis within radio navigation in Sweden have been given to ISIS students since ISIS started (ceremonies 1997, 1999 and 2001). This clearly shows that Linköping University has outstanding competence in Sweden in the navigation area.

- About 15 students started to work at SAAB after graduation.

Resource management in wireless communication systems

With the dramatic success of Internet, designing data networks using Internet components based on the internet protocol (IP) have become increasingly popular. Such networks are not traditionally designed to guarantee any quality of service; instead the 'best effort' paradigm has been ruling. Recent research and development in the Internet technology community have brought forward mechanisms to differentiate between different services and to support service quality guarantees to some extent in the network.

Through a large number of Master's thesis projects, the group has gained a well founded competence in these mechanisms, both through theoretical studies as well as requirements from various applications. Furthermore, this knowledge has been transferred to ISIS and non-ISIS companies through the thesis projects. The variety of applications and companies is illustrated by the variety of master theses in Enclosure I, where more than 10 theses have been completed at Ericsson.

Appendix A: ISIS Publications

Phase 3 2001 - 2003

This list only contains publications which have at least one ISIS PhD student or ISIS Research Associate as a coauthor

PhD Theses

[1] Henrik André Jönsson. Indexing time series data. Thesis no 757, 2002. ISBN 91-7373-346-6

[2] Johan Löfberg. Minimax Approaches to Robust Model Predictive Control. Thesis no 812, 2003. ISBN 91-7373-622-89.

Licentiate Theses

[3] Dan Lawesson. Towards behavioral model fault isolation for object oriented control systems. Licentiate Thesis no. 863, Department of Computer and Information Science, Linköping University, SE-581 83 Linköping, Sweden, Dec. 2000. Defended in February 2001.

[4] Johan Löfberg. Linear model predictive control: Stability and robustness. Licentiate Thesis no. 866, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jan. 2001.

[5] Rickard Karlsson. Simulation based methods for target tracking. Licentiate Thesis no. 930, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Feb. 2002.

[6] Per-Johan Nordlund. Sequential Monte Carlo filters and integrated navigation. Licentiate Thesis no. 945, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, May 2002.

[7] Måns Östring. Identification, diagnosis, and control of a flexible robot arm. Licentiate Thesis no. 948, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Jun. 2002.

[8] Niclas Persson. Event based sampling with application to spectral estimation. Licentiate Thesis no. 981, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec. 2002.

[9] Per Andersson. Intake Air Dynamics on a Turbocharged SI-Engine with Wastegate. Licentiate Thesis no. 934, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, 2002.

[10] Traian Pop. Scheduling and Optimisation of Heterogeneous Time/Event-Triggered Distributed Embedded Systems. Licentiate Thesis. Linköping University, SE-581 83, 2003.Linköping, Sweden, 2003.

[11] Mattias Krysander. Design and Analysis of Diagnostic Systems utilizing Structural Methods Licentiate Thesis. Linköping University, SE-581 83, 2003.Linköping, Sweden, 2003.

[12] Erik Geijer Lundin. Uplink Load in CDMA Cellular Systems Licentiate Thesis no. 1045, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Oct. 2003.

Journal Papers

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[14] Svante Gunnarsson and Mikael Norrlöf. On the design of ILC algorithms using optimization. *Automatica*, 37:2011–2016, Dec. 2001.

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[16] Fredrik Gunnarsson and Fredrik Gustafsson. Time delay compensation in power controlled cellular radio systems. *IEEE Communications Letters*, 5(7), July 2001.

[17] E. Frisk and M. Nyberg. A minimal polynomial basis solution to residual generation for fault diagnosis in linear systems. *Automatica*, Volume 37(9):1417–1424, September 2001.

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[19] Mikael Norrlöf and Svante Gunnarsson. Experimental comparison of some classical iterative learning control algorithms. *IEEE Transactions on Robotics and Automation*, 18(4):636–641, Aug 2002.

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[21] Mikael Norrlöf. An adaptive iterative learning control algorithm with experiments on an industrial robot. *IEEE Transactions on Robotics and Automation*, 18(2):245–251, April 2002.

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