NUTEK's Competence Center **ISIS**
Information **S**ystems for **I**ndustrial Control and **S**upervision
Final Report for Phase 2: 1998-2000
(Public Version)

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Föreståndare

1 Sammanfattning

ISIS är ett centrum med nio industripartners och sex forskningsgrupper, med inriktning mot industriella styr- och övervakningsproblem, och med syfte att använda och utveckla verktyg både från datavetenskap och reglerteknik.

De största utmaningarna för ett kompetenscentrum är att hålla en bra balans mellan vetenskaplig production och industriellt relevans, att producera välutbildade personer och att ha aktivt personalutbyte.

ISIS har hanterat dessa frågor med beslutsamhet. Hög standard av internationella publikationer har bibehållits, liksom hög produktionstakt av examina (Civ.ing., Tekn.lic. och Tekn.Dr.). Samtidigt har projekten gjorts i nära samarbete med industrideltagarna. Flera kommerisialiserade produkter och produktförbättringar är resultat av ISIS-projekt. Flödet av perosnal från ISIS-forskningsgrupper till ISIS-företag, liksom i den andra - mer ovanliga - riktningen har skett.

ISIS har lett till ett antal fördelar för deltagarna. Det nära samarbetet mellan industri och universitet har, till exempel, betytt att patentansökningar har lämnats in av forskargrupper som tidigare aldrig sökt patent. Avancerade signalbehandlingsapplikationer i industriella produkter skulle inte ha implemenerats utan samarbetet med ISIS universitetsgrupper. ISIS har varit en värdefull rekryteringsbas för företagen under de år då välutbildade inom IT-området har varit en bristvara. ISIS har också bidragit till ökat intesse för företagens ingenjörer att söka sig till forskargrupperna som doktorander. ISIS går hand i hand med forskarskolan ECSEL, som syftar till en bredare utbildning över spannet mellan datavetenskap och systemteknik.

I denna rapport kommer vi att tillhandahålla ett antal fakta som beskriver organisation, projekt, och resultat inom ISIS. Förhoppningsvis kommer också att framgå att ISIS har inneburit en viktig vitalisering av samarbetet mellan industri och universitet över forskningsgränserna.

2 Executive Summary

ISIS is a center of nine 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.

ISIS has dealt with these challenges in a decisive manner. A high level of international publication has been maintained, as well as a high production rate of graduate exams (MSc, Techn.Lic, Ph.D). At the same time, the projects are carried out in close contact with the industrial partners. Several products and product enhancements, resulting from ISIS projects are already commercialized, and several patent applications have been filed. The flow of people from ISIS research groups to ISIS companies, as well as in the other – more unusual – direction 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, in years where well educated people in the IT area have been scarce. Also, ISIS has spurred an interest for the engineers in the companies to join the research groups as PhD students. ISIS also operates hand in hand with a new graduate school (ECSEL) that aims at providing a broader graduate education across Computer Science and Systems Engineering.

In this report we shall give a number of facts that describe the organization, projects, and production of ISIS. Hopefully, it will also convey a major message, that ISIS has meant an important and useful vitalization of the way to cooperate between industry and university, across research specialties.

3 Summary of Some Key Numbers for Phase 2: 1998-2000

- 8 graduated PhD's
- 5 graduated Techn.Lic.'s
- 47 master theses
- 13 articles, published in refereed international journals
- 57 international conference publications
- 27 technical reports

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. In 1999 one company left and three more joined ISIS. Also, one more research group joined the center. In this section, *Basic Facts*, administrative information about ISIS will be given.

4.1 Partners

During Phase 2 the partners of ISIS were as follows.

From Industry

- ABB Automation Products AB, 721 59 Västerås
- ABB Automation Systems AB, Västerås. Joined ISIS January 2000.
- ABB Corporate Research AB, 721 78 Västerås. Joined ISIS January 2000.
- ABB Robotics AB, 721 68 Västerås
- Ericsson Utvecklings AB. Left ISIS December 1999
- Ericsson Radio Systems AB,Box 1885 581 17 Linköping. Joined ISIS January 2000
- Mecel AB, Box 73, 662 22 Åmål
- Saab AB, 581 88 Linköping
- Saab Automobile AB, Box 636 151 27 Södertälje
- Saab Dynamics AB, 581 88 Linköping

From University

- Division of Automatic Control, Department of Electrical Engineering
- Division of Vehicular Systems, Department of Electrical Engineering
- Division of Communication 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
- Laboratory for Engineering Databases and Systems, Department of Computer and Information Science

4.2 Personnel

During the years a large number of people have been involved in the ISIS projects. The personnel situation during Phase 2 is given in the tables in Appendices **??** - **??**. It lists about 75 people in industry and university that have been active in ISIS during 1998-2000, along with the number of man-months spent on ISIS projects.

The manangement structure is such that the *Director*, Lennart Ljung, with the aid of the *ISIS Sectratary*, 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 at the end of Phase 2.

Board Members

Ulf Rehme	Saab AB, chairman
Staffan Ahlinder	ABB Automation Products AB
Torgny Brogårdh	ABB Robotics AB
Olle Englund	Saab Automobile AB
Krister Forsman	ABB Automation Systems AB
Per-Erik Modén	ABB Corporate Reserach AB
Jan Nytomt	Mecel AB
Helge Persson	Saab Dynamics AB
Martin Rantzer	Ericsson Radio Systems AB

Reference Group

Petru Eles	Linköping University
Fredrik Gustafsson	Linköping University
Inger Klein	Linköping University
Mats Molander	ABB Automation Products AB
Lars Nielsen	Linköping University
Ulf Nilsson	Linköping University
Erik Sandewall	Linköping University
Nahid Shahmehri	Linköping University

Work distribution

The following table shows the number of man-months spent on ISIS projects during Phase 2, divided into different personel categories. This is a compilation from the more detailed tables in the appendices. The distribution of work over the different projects is shown in these more detailed tables. “MMx” means Man-Months for year x.

Category	MM98	MM99	MM00	Sum
PhD student	102	04	89	285
Research Associate	23	27	28	78
Professor (sim)	14	29	31	74
Industry	108	90.5	115.5	314

4.3 Budget Phase 2

To get an overview of the economy of ISIS, we first list the outline budget for the years of Phase 2 (1998-2000). In the following section the economic outcome will be described. The Unit in all tables is KSEK (1000 SEK). The expression "x (y)" means "a total contribution of x KSEK, out of which the cash contribution is y KSEK."

Available Funding

Contributor	1998	1999	2000	Sum
NUTEK:	6000 (6000)	6000 (6000)	6000 (6000)	18000 (18000)
LiTH	5495 (0)	6060 (1000)	7805 (1000)	19360 (2000)
Industrial Partners	9100 (1000)	7788 (1000)	9755 (1000)	26643 (3000)
Sum	20595 (7000)	19848 (8000)	23560 (8000)	64003 (23000)

Contributions from Industrial Partners

Company	1998	1999	2000	Sum
ABB APR	725 (50)	725 (50)	987 (50)	2437 (150)
ABB ASY	0	0	950 (50)	950 (50)
ABB RP	1000 (700)	1450 (700)	1025 (50)	3475 (1450)
ABB CR	0	0	893 (50)	893 (50)
Ericsson Radio	0	0	1650 (600)	1650 (600)
Ericsson Utv	3050 (50)	1925 (50)	0	4975 (100)
Mecel	800 (50)	800 (50)	800 (50)	2400 (150)
Saab AB	1700 (50)	950 (50)	950 (50)	3600 (150)
Saab Auto	800 (50)	800 (50)	800 (50)	2400 (150)
Saab Dyn	1025 (50)	1138 (50)	1700 (50)	3863 (150)
Sum	**9100 (1000)**	**7788 (1000)**	**9755 (1000)**	**26643 (3000)**

4.4 Economic Report Phase 2

All ISIS costs are personnel costs with overhead. The cost of a man-month is calculated as follows:

1. The sums for the LiTH work is computed with the following internal prices:
   - Professor (similar): 75 000 SEK/month

- Research Associate: 55 000 SEK/month. For 2000 the cost was raised to 70 000 SEK/month
- PhD student: 42 000 SEK/month. For 2000 the cost was raised to 50 000 SEK/month.

These sums *include*

- a 12 % general administrative university overhead
- a 8 % overhead for office space
- associated costs, computer software and maintenance, secretarial support, travel.

but *do not fully cover*

- The University's total cost for a PhD-student, which is estimated to 800 KSEK/year.

2. The companies' cost for own work has been calculated according to the NUTEK keys:
   - Senior researchers: 75 000 SEK/month
   - Technicians: 40 000 SEK/month

The actual man months paid for by ISIS during Phase 2 are listed in the tables in Appendices **??** - **??**. These also show the distribution of the costs on the different projects, as well as the cost for labor paid by the companies.

The use of the 23 MSEK cash that was available during Phase 2 is described in the following table:

Organization	Contribution	Expenditure
NUTEK	18 000	0
Companies	3 000	0
LiTH	2 000	0
LiTH PhD-students	0	12 678
LiTH Res. Ass.	0	4 025
ISIS-administration	0	450
ISIS-seminars& sim	0	600
Surplus Phase 2	0	5 247
Sum	23 000	23 000

The contributions from industry and the distribution of costs on the different projects close follow the budget plan that was set up for Phase 2 in December 1997. The main deviations are that several companies have contributed with more mon-months than originally planned, and that a surplus of cash has been generated. The main reason for the surplus has been difficulties to recruit

compentent personell, a difficulty that has been shared by many other actors on the IT arena in recent years.

Phase 2 thus leaves a surplus of 5 247 KSEK. According to the agreement with the ISIS board and NUTEK/VINNOVA these can be used during Phase 3 for recruitment purposes.

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 1998. (It has been edited in view of the new partners that have joined since then.)

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 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.

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. However, a concentration is necessary, and therefore the center has made detection and diagnosis *in industrial systems a focus. The reasons for selecting these topics as a focus are that detection and diagnosis will be of increased importance for industry, that there are still several scientific problems to be solved in these areas and that a concentrated skill in these areas is lacking both in Sweden and abroad.*

To match the industrial demands, competence is built up to develop functionality for detection and diagnosis in different parts of industrial systems:

Control Systems: *The focus is to develop efficient model based methods for error detection and diagnosis on different equipments and processes. The development is driven by projects together with SAAB Automobile AB and MECEL AB on car engines, with ABB Robotics Products AB on industrial robots and with ABB Automation Products AB, ABB Automation Systems, and ABB Corporate Research on general industrial processes. Technologies developed in these projects are residual based error detection, dynamic modeling, system identification, state estimation, iterative learning and non-linear model*

predictive control. The competence will have high potential for industrial controllers ranging from simple electric motor control to aircraft control and the control of complete industrial plants.

Measurement Systems: *The main emphasis is to develop accurate detection methods in systems with an extensive amount of complex sensor information. Industrial partners for the projects pushing this development are SAAB AB and SAAB Dynamics with integrated navigation and guidance systems as the product target. Main areas for the research are methods for nonlinear estimation and sensor fusion. This competence will have a wide spread industrial use in products relying on large amounts of sensor data, as for example navigation systems, quality test equipments, plant control systems, power network supervision systems etc.*

User Interfaces: *The detection and diagnosis aspects on the user interface are centered around error detection, error recovery and discrete system diagnosis. The developments are made together with ABB Automation Products AB for process control languages and with ABB Robotics Products AB for robot control diagnosis. The technologies investigated are state transition modeling, advanced assert programming and modeling and diagnosis of discrete event dynamic systems. Handling of errors needs to be improved in almost all kinds of industrial systems and is very important for the future.*

Databases: *Most of the methods for detection and diagnosis need some kind of models describing the system, equipment or process in question. To implement and make use of these models, which are sometimes very big, high performance databases are crucial. The database aspects studied are real-time cost models for query optimization and means for specifying timeliness and quality trade-offs in database queries, active database capabilities, methods for queries and views in heterogeneous environment and index methodology for spatial and temporal data. The database competence is very important for companies developing their own tailored embedded databases and the need for this competence will increase with the increased use of models for detection and diagnosis.*

Besides building up competence in the projects, the center will also educate people in industry and at the university, in the area of detection and diagnosis.

5.2 Problems, Progress, Plans

Problems

We have to some extent suffered from the *problem* of lack of personnel in the research groups, in particular for the Computer Science labs. That is a problem we have shared with many employers in the IT arena. Recruiting able PhD-student has meant harder work than in earlier years, and some projects, (especially the Real-Time Embedded Systems) have been postponed due to this. A related

problem is that most just-graduated PhD's leave the university for industry (often an ISIS company). This is in itself a sign of success for ISIS, but also means extra work to keep continuity in the projects. Two of the co-founders of ISIS, Anders Törne and Tore Risch, have also left Linköping University during 1999 to work industry and another university, respectively.

We have actively dealt with these problems, and during 2000 a number of new people from the Computer Science Department are joining ISIS.

Progress

The just mentioned problems have however been minor, and we believe that we have been successful in our work towards the goals outlined in the strategy document. As will be described in Sections 6 and 7, ISIS has been productive both in terms of scientific publications, graduate exams, and products and product enhancements at the participating companies. 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. See Section 7.5.

While keeping a fairly broad competence profile, we have still been able to focus on different approaches to supervision, fault detection, and diagnosis. Four out of eight PhD theses directly deal with these issues.

Plans

For the next few years the following items are essential.

- Further develop the profile for excellence and experience in detection and diagnosis.
- In particular, make use of experience from the different applications areas.
- Strengthen the Computer Science profile by recruiting new researchers to ISIS.
- Maintain the balance between scientific quality and industrial relevance in the same way as during Phase 2.

5.3 External Collaboration

ISIS has an International Scinetific 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 concerns both the relations within the research groups between ISIS and non-ISIS activities, the interaction between the different groups, and the interaction between university and industry. For management issues, see also Section 4.2.

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 compentence is "fed" also from other, and perhaps more theoreticllay 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.

The collaboration between the groups and between industry and university is manifested in the joint projects, and in joint seminars and workshops. The TKG-groups also give important cross disciplinary insights. The general technical discussions carried out there serve both the purpose of giving a deeper understand of the technical problems and applications in the company, and seeding ideas for new projects.

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 700 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 1999 is as follows:

Data Bases for Control, Modeling and Simulation

1 Real time Data Bases for Telecommunication

2 Active Query Services for Telecom Data Servers

3 Map and Terrain Data Bases for Navigation

Diagnosis, Supervision and Safety

4 Diagnosis for Car Engines

5 Fault Isolation in Object Oriented Control Systems

Techniques for Developing Integrated Control and Information Systems

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

6 Enhancement of process Control Languages

Methods for Synthesis of Control and Supervision

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 2. Project 12 was started during the 1999, but decided upon earlier.

See the annual reports for 1998, 1999 and 2000 for project summaries, and more detailed desciptions of the achievements during Phase 2.

6.2 Technical and Scientific Achievements

It is not easy to succinctly summarize the rather extensive activities of ISIS. In this section four scenarios are described that may give a picture of ISIS operations. For further descriptions, see the "production lists" later in the and the following section.

The project *Supervision and Control of Industrial Robots* has been performed in close cooperation between the Division of Automatic Control and ABB Robotic products. *Mikael Norrlöf* was hired in April 1996 as a PhD Student. He has spent about 25 % of his time at ABB in Västerås, learning the robotic application, the details of the programming language etc. An ABB 1400 robot has also been installed at the Control Laboratory at the university. Norrlöf has carried out research on Iterative Learning Control (ILC), developing several methods, and implementing them in the commercial robotics software. This had lead to several international publications, a patent application, as well as a PhD thesis to be defended in October 2000. The ILC feature is now part of the ABB robot (a press release was published in August), and it is considered to give the robot an essential competition edge. See also Section 7.4. The project is an example a long range cooperation commitment that would be difficult without an organization like ISIS.

Map and Terrain Data Bases is a project carried out by *Ling Lin* at the Engineering Data Bases laboratory. Lin started the project in October 1995 and worked with Niclas Bergman on the Data Base aspects of terrain navigation in cooperation with SAAB Dynamics. She developed new important techniques for handling sequences of data, and presented the results at several international conferences. She defended her PhD thesis in the spring of 1999, and now works with Ericsson.

Niclas Bergman studied the signal processing aspects of the terrain navigation problem in close cooperation with SAAB Dynamics. He developed new algorithms that were not based on linearization thus giving excellent global properties. These new techniques have been central to achieve significantly better functionality and performance for SAAB's commercial navigation system TERNAV. (See Section 7.4.) The application also gave rise to several theoretic problems regarding achievable accuracy, which Bergman also solved, and published internationally. An overview of the results were published in the high profile journal *IEEE Control Systems Magazine* in May 1999. Bergman was hired as a PhD student at the start of ISIS in October 1995. He finished his PhD in April 1999, spent a post doc period in Melbourne and now works at Celsius AB, a SAAB Company.

The project *Signal Interpretation and Control in Combustion Engines* has been performed in close cooperation between the Division of Vehicular Systems, Mecel AB, and Saab Automobile AB. *Lars Eriksson* started the project in 1996.

At first he spent time in Åmål learning the basic ion-sense technology. Thereafter, he built the laboratory environment in Linköping and also worked goal oriented towards the project milestone: Closed-loop control of ignition timing under varying conditions. This was new. It had not been demonstrated by others except when using (expensive) extra sensors. Here only existing sensors in combination with signal interpretation were used. In addition models and methods for improving performance have been studied and developed. The work has lead to several international conference papers, journal publications, one patent, as well as a PhD thesis that was defended in April 1999. Lars Eriksson continues in ISIS and the project is thus an example of a research cooperation that was initiated in ISIS and is now growing.

6.3 Scientific Papers

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

In addition, several PhD, Techn Lic, and M.Sc theses have been completed as described in the next section.

6.4 Examination 1998-2000

All ISIS projects involve at least one graduate student. Graduate studies can be completed as a Techn.Lic exam (which is about 50% of a PhD exam.) or as a PhD degree. In addition a number of MSc theses have been prepared within or in close cooperation with ISIS project. In this section we list the PhD and Techn.Lic degrees that have been completed within ISIS. For the MSc exams we refer to Appendix A. Moreover, see Section 7.6 for a description of how MSc theses have been used in a systematic way to build up competence and a simulation platform at an ISIS company.

PhD-degrees:

- M. Ronström: Design and modelling of a Parallel data Server for Telecom Applications. 1998.
- Niclas Bergman: Recursive Bayesian Estimation: Navigation and Tracking Applications, May 1999.
- Lars Eriksson: Spark Advance Modeling and Control, May 1999.
- Mattias Nyberg: Model Based Fault Diagnosis: Methods, Theory and Automotive Engine Applications: June 1999.
- Magnus Larsson: Behavioral and Structural Model Based Approaches to Discrete Diagnosis, December 1999.
- Lin Ling: The IP Index, March 1999.

- Mikael Norrlöf: Iterative Learning Control: Analysis, Design, and Experiment. Ocotber 2000.

Licentiate degrees:

- 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.
- Dan Lawesson: Towards behaviorial model fault isolation for object oriented control systems, December 2000.

Degrees partly completed within ISIS:

PhD-degree:

- M. Sköld: Active Database Management Systems for Monitoring and Control.

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.

In the undergraduate School of Engineering at Linköping University, special study programs ("profiles") have been established within Electrical Engineering and Computer Engineering specialities. These profiles are called "Control and Information Systems", and the Director of ISIS is also responsible for their curricula. 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 describes the industrial committment of ISIS, the expectations of our industrial partners, as well as what ISIS has achieved in terms of useful industrial results and people flow between university and industry.

7.1 Industrial Involvement

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

- Directly in ISIS projects as listed in Appendix **??**.
- In technical discussions, outside the projects, in so called TKG-groups (Technology Contact groups).
- In seminars, workshops, mini-courses, arranged by ISIS.

7.2 Industrial Partners' Expectations: Strategic Goals for Participating Companies

Each of the participating companies have written as Strategy Document that describes the company's reasons for joining ISIS, as well as its expectations for the involvement. These documents are given in Appendix B.

7.3 Commercialization and Technology Transfer Activities

One main objective with a competence center is to provide technology transfer from the university to the companies, as well as influx of new problems and ideas into the university. The technology transfer can take a number of different shapes:

- General exchange of ideas, leading to better understanding, knowledge and higher competence.
- Explicit products or product enhancements that can be traced directly to ISIS projects.
- Exchange of personnel.

We shall in this section comment on the two last, more concrete and demanding items.

7.4 Results Made Into Products

We quote statements from some of the participating companies:

ABB Robotics

"The first step of the technology of Iterative Learning Control (ILC) (Project 7) for high accuracy robot path generation has been successfully transferred to ABB Robotics and is now introduced in an ABB product for accurate material cutting using standard industrial robots. The first delivery to a customer in the US has already been made and thanks to the ILC technology ABB is now considered to have the robots with the best price/performance for the fast growing laser cutting market. Besides laser cutting the interest is very big to use the same technology also for water jet cutting, plasma cutting and laser welding. With the possibility of patent protection and with no other robot manufacturer having the same ILC functionality as ABB today, there will be good opportunities for ABB to obtain a big market share on the fast growing high precision manufacturing market, which is expected to generate a volume of about 4000 robots/year for robots with the accuracy achieved with the ILC functionality. This break through through would never have been possible for ABB Robotics without the long term development initiative for Iterative Learning Control at ISIS 4 years ago.

At present ABB also applies ILC concepts to robot assisted assembly and to metal grinding. ILC installations for robot assisted assembly of car body frames and for grinding of jet engine turbine blades are now made at customer sites in the US. The potential robot market for assembly and grinding is even bigger than for high precision manufacturing.

There is now a growing interest in diagnostics and fault detection at ABB Flexible Automation and ABB Robotics. Therefore, the competence built up at ISIS the latest years (Project 5) in the areas of model-based fault detection, fault isolation and trend analysis will be very useful for ABB. During the next 2 years it is expected that ISIS competence in these areas will be transferred to ABB to be key components in the next generation of ABB Robotics embedded diagnostics and fault detection system."

SAAB Aircraft

"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 Dynamics

"The work of Niclas Bergman on Bayesian filtering (Projects 9 and 11) has been directly applicable to our products. The basic research that Bergman has carried out within ISIS has continuously been transferred to SAAB Dynamics, where the method has been further developed, so that manifold filters can be combined with Bayesian statistics. Within SAAB Dynamics, the Terrain navigation system TERNAV – which is part of the navigation system for missiles and UAVs – has achieved significantly better functionality and performance."

SAAB Automobile

" Mattias Nyberg's thesis on detection of very small air leakages (Project 4) 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 basic method that we use for development of new functionalities in our motor control system (Trionic) and for diagnosis and control.

The use of the ionization current signal (Project 10) to control the spark advance is of central interest to SAAB Automobile. It is likely that we will implement this method as soon as the computational capability is available."

ABB Automation Products

"The results of the ISIS projects that ABB Automation Products has participated in has not yet showed up in any released products. However, one recently released product, the multivariable model predictive controller, 3dMPC, owes some solutions to discussions that have taken place during ISIS meetings (but not related to any specific project). The solutions are methods to handle merged data sets in system identification, and a parameterization for state space models, also used in the identification. These are just small spin-off effects of our ISIS participation, but in our opinion is the opportunity that ISIS gives for informal discussions on problems within the ISIS area of competence that might arise, whether or not directly related to an ongoing ISIS project, a very important element of the center."

7.5 Flow of People

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 Aircraft after receiving his Civ.ing. (M.Sc) 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 Tech. Lic. degree in 1997, and then became the head of the SAAB navigation group.
- *Per Johan Nordlund* has worked 3 years at SAAB Aircraft and is now an ISIS funded Industrial PhD student, spending 60 % of his time on the Sensor Fusion project.
- *Rickard Karlsson* has worked 3 years at SAAB Dynamics, and is now an ISIS funded Industrial PhD student, spending 60 % of his time on the Sensor Fusion project.
- *Ingemar Andersson* has worked at MECEL for 2 years, and is now an Industrial PhD student in the Vehicular Systems group. He is not funded by ISIS, but closely connected with the ISIS projects.
- *Per Andersson* worked 2 years at SAAB Training Systems, and has now moved to be a PhD student at the Vehicular System group, funded by ISIS for the project Signal Interpretation and Control in Combustion Engines.
- *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, closely related to Projects 1 and 2. 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

- *Magnus Larsson* finished his PhD thesis in December 1999, within the project Fault Isolation In Object Oriented Control Systems, in close co-operation with ABB robotics. From April 1 2000 he will work at ABB Robotics.
- *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.

- *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.
- *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.

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

Master Theses (examensarbeten) 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 a 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 15 master theses have been performed. Perhaps inspired by this effort, other departments at SAAB, and other companies have increased their number of master projects significantly. The block diagram below shows the structure of the simulation environment, where also target tracking is included. All 50+ theses related to ISIS projects are referred to in the blocks. Main companies are: SAAB Aircraft, SAAB Dynamics, FOA, Celsius Tech, Luftfartstyrelsen and Ericsson Microwave.

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

[**25**] The Polhem price 1997 for best master thesis in Sweden.

[**10**] Radionavigationsnämnden 1'st price 1997.

[**17**] Radionavigationsnämndens 2'nd price 1997.

[**37**] Radionavigationsnämndens 1'st price 1998.

[**33**] Radionavigationsnämndens 2'nd price 1998.

The interaction of personnel with industry, mainly SAAB, is also something that we want to stress:

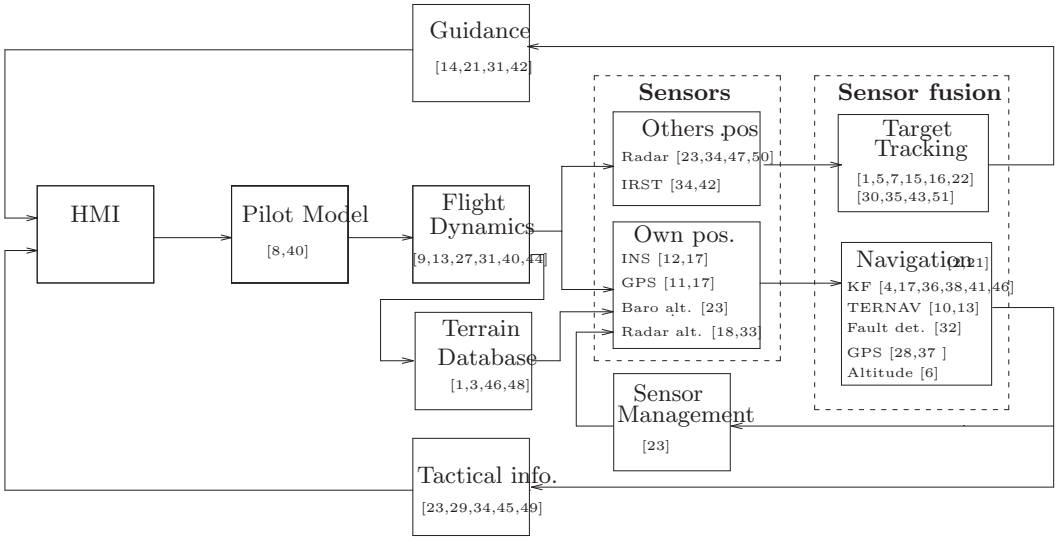

Figure 1: Block diagram for the connection the about 50 Master Theses that relate to the ISIS nagivation and sensor fusion projects. The actual theses are listed in Appendix A of the annual report for 1999.

- The following students are now working at SAAB: [2,6,9,15,17,20,22,25(x2),32,37,39,39].
- Jan Palmqvist, once a MSc from LiTH, worked for SAAB for ten years, before entering ISIS as an industry PhD student 1996. He obtained the licentiate degree 1998. After that, he was promoted to Head of the navigation department at SAAB.
- Predrag Pucar started at the same department after his PhD in Automatic Control.
- Niclas Bergman did a PhD in ISIS within the Terrain Navigation project and is now working for Celsius Tech, developing his navigation algorithms.
- The fall 1999 four industrial PhD students started in the "Sensor Fusion" project, two of them belonging to ISIS (one from SAAB Aircraft, one for SAAB Dynamics). Their projects and methods are partly overlapping, and close interaction is expected.

A ISIS Publications 1998-2000

This list only contains publications which have at least one ISIS-student as a coauthor

Ph.D. Theses

[1] M.Ronström. *Design and Modelling of a Parallel Data Server for Telecom Applications*. Dissertation no. 520, Linköping Studies in Science and Technology, 1998.

[2] Niclas Bergman. *Recursive Bayesian Estimation: Navigation and Tracking Applications*. PhD thesis, May 1999.

[3] Lars Eriksson. *Spark Advance Modeling and Control*. PhD thesis, Linköping University, May 1999.

[4] Mattias Nyberg. *Model Based Fault Diagnosis: Methods, Theory, and Automotive Engine Applications*. PhD thesis, Linköping University, June 1999.

[5] M. Larsson. *Behavioral and Structural Model Based Approaches to Discrete Diagnosis*. Phd thesis 608, Department of Electrical Engineering, Linköping University, Linköping, Sweden, December 1999. Can be acquired at http://control.isy.liu.se/publications/.

[6] Lin Ling. *Management of 1-D Sequence Data - From Discrete to Continuous*. Dissertation no. 561, Linköpings universitet, Sweden, 1999.

[7] Mikael Norrlöf. *Iterative LearningControl: Analysis, Design, and Experiments*. PhD thesis, Linköpings universitet, Oct 2000.

PhD Theses, Partly completed within ISIS

[8] M. Sköld: *Active Database Management Systems for Monitoring and Control*, PhD Thesis No 494, Linköping University.

Licentiate Theses

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Patent Applications

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B The Companies' Strategic Documents for Joining ISIS

ABB Automation Products AB

The strategic goal for ABB AP's participation in ISIS is to increase our knowledge in some core competence areas, to influence the research directions in areas vital to us and to use the scientific contacts built up as a way to recruit specialized personnel and to use ISIS personnel as natural speaking partners. As a leading manufacturer of process control equipment it is of vital importance that we have spearhead competence in the areas of control engineering and supervision. We strongly believe that ISIS can help us to build up and maintain that competence. Another important area is process control language development, as the control language and accompanying tools are the key factors determining how easy it is to configure our system and to maintain and reuse control solutions. The concept of the TKG-group fulfills an important role to broaden the network between ISIS and ABB AP. It is used as a tool to spread information and come up with new ideas regarding areas of cooperation and new projects. To measure the success in achieving the goals with the ISIS membership is difficult in a strictly quantitative way, and the evaluation will have to be largely qualitative. Some quantitative ways to measure could be to count, in some way, the direct use in our development of spin off results from ISIS projects (the counts could be, number of implemented functions, number of lines of code implemented, man time saved or some other appropriate measure) and number of people employed as a result of ISIS contacts.

ABB Automation Systems AB

In process industry in general, and the paper industry in particular, there is a rapidly growing need for increasing the efficiency of existing plants and machinery. Frequently this type of work is termed process optimization, even though the process may not always be optimized in the strict mathematical sense of the word. For a large paper mill a successful process optimization project could generate savings and profit increase in the order of magnitude of 5-10 million US dollars per year. Savings typically come from increased product quality, decreased reject, decreased consumption of energy and raw material, and increased productivity and up-time. Some key technologies in process optimization are diagnostics (both on-line and off-line), control optimization, advanced control and process modeling.

ABB Automation supplied services and automation solutions to the process industry and other industries. To be successful in doing this, it is vital that we have access to, and understanding of, the latest development in the technical key areas mentioned above. Our participation is ISIS is a good way of leveraging our own research and development projects, in core technologies. Since several of the Linköping researchers a world leading in their respective areas, such as process modeling nad diagnostics, we believe that ISIS is an excellent R&D

partner.

ABB Corporate Research (representing ABB AB)

In ABB Corporate Research we view ourselves as having a role of bridging the gap between recent research results and their industrial application within ABB. In this role it is essential to have close relations with universities who are in the front in their area. Therefore, our participation in the competence center is expected to give us great benefits. The joint competence in the center and the influences from the other industrial partners will be very valuable. Projects run within ISIS should bring the methods and ideas related to industrial control a first step closer to real application within ABB .

Some specific areas of where we could benefit from ISIS are: Data Quality & Signal Diagnostics, Data Mining & Modeling, and Diagnostics for Process Components and Process Sections. Potentially any aspect of advanced control or optimization that is relevant for industrial control in the ABB perspective could qualify for a project.

It is our hope that we may inspire research in directions which we find important and believe could lead to improved industrial control.

It is also expected that the participation will contribute to a positive image of ABB in the eyes of both students and others who appreciate the competence center.

ABB Robotics Products AB

In 1996 ABB Robotics Products AB started an ISIS-project on Supervision and Control of Industrial Robots. The main reasons for joining ISIS were to build up competence not available inside ABB Robotics and to make use of the scientific networking possibilities at LiTH.

Industrial robots consist of several high technology components and much of the success of being a robot manufacturer depends on the ability to integrate these technologies into an easy to use product with high performance and high reliability. One key technology is control engineering and very important for the future competitiveness is high performance control and supervision. The strategy of ABB Robotics Products AB is to make use the ISIS activities for evaluation of new technologies, for which in-house competence is lacking, and for transferring knowledge from the university to the company. Of great importance is to make the transfer over a longer time period to make the engineers at ABB Robotics Products AB used to the new technology in an early stage of the research and to avoid NIH-effects. In order to have a product oriented research at ISIS, it is also very important that the PhD students work part of their time at the company. This strategy also makes it possible to find spin-off effects, where applications of new technology can be found and be implemented in the ongoing product development.

One part of the strategy is to have measures, which can be used for the evaluation of the results of the activities at ISIS. The measures used by ABB

Robotics Products AB are the number of robot control functions resulting from spin off activities with connections to the project, the number of functions implemented as a direct result of the project, the number of PhD students employed and the number of undergraduate students employed. If any of the resulting new controller functions can be traced as a direct reason for selling a specific number of robots, this number will also be used in the evaluation.

Concerning the networking possibilities, the TKG-group concept is used as a strategic means to find new competence areas of future importance for ABB Robotics Products AB. The scientific areas identified by the TKG-group may result in new ISIS-projects. One example is an ISIS-project on discrete system modeling for robot controller diagnosis which started in 1998. Other areas identified by the TKG-group are embedded real time object oriented databases, task oriented programming paradigms, programming language extensions for error recovery and modeling and supervision of arc welding processes.

B.0.1 Ericsson Radio Systems AB

Future, and also the current radio network systems, are becoming increasingly complex with many dependent functions that interact with each other in a partly unknown way. For example, from a control theory perspective, the WCDMA system consists of many closed loops that affect the same power resource, but on different time scales. If the functions interact badly, instability problems and loss of system capacity will occur. While the 2nd generation operators have problems with optimizing their current networks, with basically one type of traffic channel and more or less one type of service, the situation will not be easier with the very flexible WCDMA system. This is particularly true since the radio access technology is novel for most operators and since many new inexperienced operators will run 3G networks.

Ericsson Research and Division of Automatic Control, ISY, Linköping University, have a mission to apply control theory aspects on adaptive radio network control. In other words, we want to apply control theory on self-configuring systems (SCS). The goals are to

- Improve system performance by online RN optimization
- Reduce OM costs by automatically tuning radio network parameters
- Provide operator choice between different policy based tradeoffs

To achieve these ambitious goals we conduct, and plan to conduct, activities within the following sub areas:

- Identification and modeling of the radio network, based on control theory methodology.
- Develop adaptive radio network algorithms that automatically adapts to varying conditions, e.g., changing traffic or radio propagation conditions.

- Develop high level control algorithms with operator intuitive input. These algorithms control the conventional radio network algorithms based on policy management operator input.

Mecel AB

Within the business area "Engine & Powertrain" at Mecel AB, engine control and diagnosis have always been the core business. We see our participation in the competence center ISIS as an effective way to address these issues. To provide valuable information for advanced engine control, combustion feedback through ion current sensing has become very important. In 1984 Mecel filed the first basic patent in the area of ion current sensing in an internal combustion engine. The technology was developed to include some base functionalities such as cylinder identification and pre-ignition detection. The first system with this functionality was introduced in Saab cars in 1988. The functionality was further developed, and the more complex knock detection function was introduced in the model year 1993. Over the years we have found that the ion current signal contains a lot more information than what has been exploited so far. Information about air/fuel-ratio, in cylinder pressure, cycle to cycle variations and EGR-content (Exhaust Gas Recirculation) are examples of combustion data that we believe could be extracted from the ion current signal. Within Mecel we do not have the competence to do signal interpretation of the complex signals we have to deal with. The signal is complex not only because of the wave shape itself, but also because of the dynamic effects, fuel variety, environmental impact and engine ware. One ISIS-project is defined within this area and very encouraging results have already been presented. An other area of interest is on board diagnosis. Legislation such as OBDII (On-Board Diagnosis II) is continuously becoming more stringent in order to protect the environment from pollution due to system failures. New techniques have to be developed in order to fulfill future system requirements. One ISIS-project is defined within this area, where model based diagnosis successfully has been demonstrated. As a member of ISIS we are starting to build up competence within these areas. The network that we build up through project work and TKG-groups is important for us in the technological evolution within these areas, and we also see the network as an important source for recruiting skilled personnel.

Saab Automobile AB

The background for Saab Automobile's interest in advanced control and diagnosis can be described as follows: In 1985 Saab started development of an Engine Management system (EMS). This was originally meant for experimental use, to make it possible for Saab to have shorter lead-times developing different functions and control strategies. The system was very successful and it was decided that the EMS should be further developed to be used for production cars, Model year 1993 "Trionic 5" was introduced controlling the 2.3 liter Turbo engine in the Saab 9000 vehicle.

Five years later the next generation of Saab EMS, "Trionic 7" was introduced in the Saab 9-5. The Trionic 7 implements an airmass based control strategy with ion sense, cylinder individual knock control and electronic throttle control. It also features full diagnose capability.

1996 Saab joined ISIS in the project "Diagnosis for Car Engines".

What is Saab Automobiles strategy with ISIS?

- To achieve perfect drive-ability and low emissions and fuel consumption the EMS needs to implement a number of robust and accurate controller algorithms. Saab wishes to benefit from the known competence in ISIS in the filed of controller algorithms, to be able to further develop the turbo-charged engine concept
- The EMS software also needs to implement full diagnose capability according to environmental legislation. In the field of diagnose algorithms Saab and ISIS have a successful project (see Project 4) concerning are intake leakage detection. Since the environmental legislation demand increases, so does the demand for better diagnose algorithms. For SAAB, it is very important to develop diagnose algorithms to have the possibility to use new components to further improve, emissions and fuel consumption.
- The wide competence span within ISIS makes it possible for SAAB to share results of other research projects which may be useful in the field of engine development. These research results would otherwise require much more effort for SAAB to obtain.
- We also see a very good opportunity to meet students and show students within ISIS and LiTH that Saab Automobile in Södertälje offers challenging career opportunities in the complete range of combustion engine technology.

Saab Dynamics AB

How does the ISIS Competence Center fit into the Saab Dynamics strategy? Saab Dynamics is a company competing on an international, military market with high performance products. These products use a great number of different technologies that we have to be able to handle. It is a small company in relation to most of our competitors. The solution to this is to focus on a few in-house core technologies and on networking to handle all the necessary technologies. To be competitive we have to come up both with efficient functional (an hopefully innovative) designs and also make a good hardware/software implementation.

The area of interest with relevance for ISIS is:

- Autonomous decision-making, navigation, guidance&control of flying vehicles
- Signal-and image processing of information from high resolution, electromagnetic sensors in moving platforms for detection, classification, identification and tracking of moving objects in varying environments.

- Implementing the functions in efficient software.

Our participation in ISIS is aimed at keeping us on the international forefront in the functional design area noting that ISIS competence areas cover some of our core competences. More specifically our purpose with joining ISIS is:

- We want to get help to follow the forefront of the relevant research activities internationally.
- We want to be able to influence the selection of research topics at LiTH so that they are reasonably close to our possible future products.
- We also want to participate in order to be able to put in industrial aspects into the work.
- We want the transfer of knowledge to us be deep enough that we can use it confidently in our future products.
- We want to keep continuous and task-oriented relations between our application-engineers and the researchers within ISIS.
- We want ISIS to be an input channel to all the included areas for upcoming issues outside the defined research projects.
- We want to be seen and known at the University as an interesting employer.

Saab AB

Saab Aerospace has been working with integration of airborne computer systems since the design and development of he Viggen aircraft started in the beginning of the sixties. From the basic design integration principles then established methods and tools for system development have been successively improved upon in order to handle the increasing system complexity. Today the system in the Gripen aircraft has a complexity characterized by many functional requirements and interdependencies, real time functionality, linear and nonlinear control, sensor fusion, logics and safety hazardous functions. In the future a strong trend for further increase in system performance and complexity is anticipated. This is necessary if the Gripen system is to maintain its competitiveness over the 20 years to come. The same trend is foreseen for the next generation of air vehicles. Thus there is a need for Saab to continue a long term improvement of his competence in the area of system integration. To succeed in this very long term competence development a good working relationship between Saab and University is of major importance. The Competence Center ISIS has a program that focus on research in an area that is very essential for our ability to develop integrated real time airborne systems. ISIS offers a way of cooperation between University and industry that suits Saab Aerospace very well.

Based on the above the following aspects are important:

The research projects shall be in areas with central, long-term activities in Saab Aerospace and special interest is given to: · Sensor and information fusion. · Decision support. · Diagnosis and detection · Coupled control with applications in navigation and aircraft control

In the collaboration special focus shall be given to: · The use of master students as a way to transfer knowledge. · The research projects must be related to on-going development at Saab. · There should be active contact persons at Saab Aerospace in every area of interest.

Finally an important aspect of ISIS is that it helps Saab Aerospace in being recognized as an interesting employer.