NUTEK's Competence Center **ISIS** **I**nformation **S**ystems for **I**ndustrial Control and **S**upervision Report Phase I, November 1, 1995 - December 31, 1997

1 Summary

The first phase of ISIS has resulted in well established links between the participating companies and the research groups at LiTH (Linköpings Tekniska Högskola). The main activities within ISIS has been the *research projects.* These are chosen to be of central importance for the participating companies and many of the project results are of immediate industrial significance. The perhaps most difficult balance to strike within the competence center is to carry out research at the international frontier and deliver high quality theses, at the same time as the results are of direct use and interest to the participating companies. We feel that we have been successful in finding this balance during the first phase of ISIS. Five Licentiate Theses and two PhD these have been produced, as well as some 15 international publications, in close cooperation with the participating companies.

In addition to the projects, ISIS runs so called TKG-groups which aim at a broad, not project-oriented, contact surface with the companies. These consist of some 6-8 people from the company in question and representatives from the research groups. ISIS also runs a series of seminars and half-day workshops.

For more information about ISIS, visit our WWW-site:
`http://vir.liu.se/isis`

2 Some Highlights

More detailed descriptions of the projects and activities will be given in the sections to follow, but we may point to the following *examples*:

- Four Licentiate Theses have been completed, funded entirely within ISIS. In addition, one licentiate thesis and two PhD theses have been completed, partly within ISIS.
- Ericsson Utveckling AB has started a new project (NDB Cluster) to develop a reliable and high-performing database system targeted for use in telecom systems. The project leader, Mikael Ronström, has finished his PhD within ISIS, and the project relies on ISIS-cooperation.
- A discovery how to diagnose small leakage in the air intake of SI-engines is considered to have substantial potential, especially for turbo engines.

The method was developed by Mattias Nyberg and a patent application has been filed.

- Jan Palmqvist who defended his Tekn. Lic. thesis within the ISIS navigation project is now head of the navigation department at SAAB Military Aircraft.

- A SAAB turbo engine as well as an industrial robot ABB IRB 1400 have been installed in the research laboratories at LiTH.

These highlights are well in line with the goals set up at the start of ISIS, to have a high production of post-graduates, and work with problems of central importance for the participating companies.

One might ask what are the benefits of organizing the research and contact activities within a competence center instead of separate projects: The main benefit of the center is that it provides a framework for future projects. The "social network" as well as the framework for funding, formal agreements etc. are already established, which makes it much easier to develop new ideas and start new activities. Our TKG-groups play an important role in this context. In addition, ISIS is a method-oriented (rather than product-oriented) network, which means that it brings together companies that otherwise would not have cooperation. These contacts have also proved to be valuable.

This report from phase I is organized as follows. In Section 3 a strategy statement for ISIS is formulated. This is based on a two-day strategy meeting for Phase II, held with the Board and the Reference group. Section 4 lists individual Policy statements from the participating companies, which describe the reasons why they have chosen to cooperate with ISIS. Section 5 lists the projects and the obtained results, while Section 6 contains information about the administrative set-up.

3 The ISIS Strategy Statement

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 Industrial Systems 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 Industrial Systems 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 competence is developed in collaboration with Ericsson. 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.

4 Strategic Goals for Participating Companies

In this section each of the participating companies expresses their own view of why they choose to work within ISIS.

4.1 ABB Industrial Systems AB

The strategic goal for ABB ISY'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 ISY. 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.

4.2 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.

4.3 Ericsson Utvecklings AB

The primary reason for Ericsson Utvecklings AB's joining ISIS was the competence available at the Department of Computer Science (IDA) at Linköping University. It was also of interest for ISIS to be able to use actual problems at Ericsson within databases as well other areas.

The database project has developed considerably faster than could be envisioned at the formation of ISIS. Today the project can be considered very successful from an industrial as well as academical point of view. Mikael Ronström will present his Ph.D. thesis shortly. The cooperation between IDA and Ericsson Utvecklings AB will be enriched further by the delivery of an Ericsson prototype to IDA.

The aim at Ericsson Utvecklings AB is to achieve deepened contacts with Swedish universities. This makes the already established cooperation within

ISIS even more interesting. In addition to the project mentioned earlier, we strive to find other areas of cooperation within ISIS, presently the area of most interest is the project on diagnosis.

4.4 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.

4.5 Saab Automobile AB

The background for Saab Automobile's interested 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 fro 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 Chapter 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 make sit possible for SAAB to share results of other research projects which may be useful in the filed of engine development. These research results would otherwise require much more effort for SAAB to obtain.
- We also see aa 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.

4.6 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. 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.

4.7 Saab AB

Saab Military Aerospace has been working with integration of airborne computer systems since the design and development of the Viggen aircraft started in the beginning of the sixties. From the basic system 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 function, linear and nonlinear control, logics and safety criticality.

For the future a strong trend for a further increase in system complexity is anticipated. This is necessary if the Gripen system is to maintain its competitiveness over the 25 years to come. The same trend is forseen for the next generation of air vehicles. Thus there is a need for Saab to continue a long term improvement of this 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 (Information Systems for Industrial Control and Supervision) has a program that is focused on 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 us very well. In the past two years we have taken active part in ISIS research projects on airborne navigation systems. The participation has not only been useful for our short term product development, but has also generated more general knowledge in signal processing for sensor data fusion and in diagnosis of system integrity and accuracy. There is also an expectation that courses in undergraduate education will benefit from the ISIS project.

5 Project Reports

5.1 Real-Time Data Bases for Telecommunication

Background and Goals This project deals with the particular problems that are special for query processing in a real-time database system for telecom and control applications.

The purpose of the project is to develop a number of database services that are important not only for telecom databases, but also for other applications of interest for ISIS, such as control applications. The kind of services we have in mind are:

- High-level queries to specify general searches and data views against the database. Such services will, e.g., make it possible to specify and use more or less complex billing policies for a telecom service provider.
- Active database capabilities where queries are continuously monitored for their current results. For a telecom service, e.g., the cost of the service can be continuously monitored while the service is progressing, and the customer will always be able to immediately see the cost. The technique would also allow the customer to specify a maximum cost and be informed when that limit is approached.
- The services will have to be provided in a reliable way, so that recovery and take-over actions can be made if a system crash occurs.

The project is connected with the project NDB Cluster at Ericsson (by Mikael Ronström et al) to develop a reliable and high-performing database system targeted for use in telecom systems. In the proposed work in this ISIS project we will also look at query processing, active databases, and other aspects of this kind of technology. See also [7]

Database Management Systems (DBMSs) contain declarative query languages. A query in such a language is translated by the DBMS into an execution plan, which is a procedural form of the query, and which can be executed step by step by the system.

With our approach, the user will be able to provide alternative versions of a query, with different real-time performance and quality. At run-time, based on the available real time to execute the query, the system can choose the highest-quality execution plan. This is called *performance polymorphism* and is elaborated in [22].

Status and Results The work on using AMOS as a query processor with with the NDB Cluster as a back-end has begun with studies of how to integrate the two research platforms. The work has not entered an implementation stage because of delays with the NDB-API.

AMOS' declarative query language was extended to be able to specify such performance-polymorphic queries. We implemented a performance-polymorphic query optimizer[22, 23], based on the query optimizer in AMOS. The cost-based query processor of AMOS was modified to generate several execution plans of varying quality for a given query, along with the expected worst-case time to execute each plan. The optimizer then finds the best execution plan within this space, or at least a good one if a heuristic function is used, according to some goal function that has to be specified for that query.

The forthcoming Licentiate Thesis by T.Padron-McCarthy [32] covers this subject. Martin Sköld's thesis [6] on active database (ADBMS) technology has direct relevance to telecom applications.

5.2 Databases for Integrated Navigation Systems

Background High-precision navigation systems require databases with high performance and reliability. They furthermore require spatial and temporal data representations and query facilities.

An example of this is when an aircraft senses its moving direction and height (its trajectory) while it is flying. By comparing this information with a Terrain Elevation Database, the aircraft can determine(locate) where it is. This kind of processing must be very fast and database indexing techniques are promising here.

Goal The project aims at developing database support for navigational applications. In particular we study how to index and query spatial and temporal data in a DBMS for navigational applications. We are developing indexing techniques for fast access to such databases.

Status and Results A time sequence is a discrete sequence of values, e.g. temperature measurements, or trajectories, varying over time. Conventional indexes for time sequences are built on the time domain and cannot deal with inverse queries on time sequences (i.e. computing the times when the values satisfy some conditions). To process an inverse query the entire time sequence has to be scanned. A new indexing technique, *the IP-index* has been developed. It is a dynamic indexing technique for large 1-D sequences on the value domain. It supports interpolation assumptions on the sequences, i.e., it can be used to query implicit values in addition to explicit values. It can be implemented by regular ordered indexes such as B-trees. It dramatically improves the query processing time of inverse queries compared to linear scanning. For periodic time sequences that have a limited range and precision on their value domain (most time sequences have this property), the IP-index has an upper bound for insertion time and search time. This work has produced two conference papers [16, 17] and a Licentiate Thesis [2].

We have investigated how to use the IP-index in the terrain-aided navigation to improve the real-time performance. Without the IP-index the location has to be performed by scanning the map. With the IP-index, the location problem can be solved more efficiently. The performance measurements were carried out in a main-memory database AMOS using a real map and 50 synthetic track files. The measurements show that the IP-index has good "settling time" for finding a small starting region for the Baysian approach (described in Niclas Bergman's Lic. thesis [1]). The results are shown in the paper "Using a Sequential Index in Terrain-Aided Navigation" published in CIKM'97 [17].

Note that it is outside the scope of this project to develop the matching algorithm itself. We only investigate how the search can be improved by using the IP-index (for a given matching algorithm).

5.3 Diagnosis for Car Engines

Project Description and Goal On-board diagnosis of car engines has become increasingly important because of environmentally based legislative regulations such as OBDII (On-Board Diagnosis). Other reasons for incorporating diagnosis in vehicles are repairability, availability and vehicle protection. The techniques used in production vehicles are mainly based on limit checking and active diagnosis. Active diagnosis means that, during special operating conditions, the engine is manipulated in such a way that faults will be detected. Active diagnosis is for example used during idle. These techniques are insufficient to fulfill the upcoming more restrictive regulations. Further, when developing better engine control systems, the diagnostic requirements together with today's diagnosis technology have shown to be a limiting factor. It is therefore desirable to find new diagnosis techniques which perform better and do not rely on special operating conditions and active diagnosis.

One way to increase the performance of the engine diagnosis system may be to use model based diagnosis in which more process knowledge is used in the form of a mathematical process model. The diagnosis can, to a larger extent, be performed passively and be applied over a wider operating range if a model is available.

Project Results

- A new Saab turbo engine was delivered to LiTH 960520. The engine test cell and laboratory was rebuilt, during the summer and early fall, to house two engines instead of one as before. The engine bench has been reconstructed and the ventilation system has been modified and expanded with extra ventilation for the inter-cooler. The electronics and software has been installed and the system is in full operation.

- In parallel with the reconstruction, the existing SAAB 2.3 liter naturally aspirated engine was used in a case study. A diagnosis system, including modeling and residual generation, has been developed for the air intake system. A model based approach is used. The diagnosis system is based on a non-linear semi-physical model and uses a combination of direct redundancy and diagnostic observers. It is capable of detecting and isolating faults in the throttle actuator, throttle sensor, air mass flow sensor and pressure sensor. The scheme has been experimentally investigated and validated in the laboratory. This work has resulted in a paper for the 1997 SAE conference, Model Based Diagnosis for the Air Intake System of the SI-Engine [20].

- Inspired by the joint industrial and academic ISIS symposium on diagnosis, supervision and safety in March 1996 several ISIS participants (from academia) have joined in an informal working group. The outcome is a report on approximately 100 pages, [31]. The report collects some of the industrial perspectives within ISIS, and reviews quite a number of possible techniques from the research literature.
- The 1997 SAE paper raised some fundamental questions regarding structure and design of diagnosis systems. Among these questions were selection of residuals, selection of thresholds, and how different residuals should be combined to achieve good diagnosis performance. These issues were studied and resulted in a proposed systematic and automatic scheme for design of model based diagnosis systems. The scheme has been successfully applied and experimentally validated on the air intake system of the SI engine. This work has also resulted in a paper for the 1998 IFAC Workshop on Advances in Automotive Control, [19].
- In September 1997 Mattias Nyberg defended his Licentiate Thesis, [4].
- One important diagnosis problem in SI-engines is diagnosis of leaks in the air intake system. The reason is that leakages will cause increased emissions and loss of power. Model based diagnosis methods were applied to this problem which has resulted in a diagnosis scheme that is able to detect and distinguish between leakages before and after the throttle. The method has been demonstrated on a production turbo-charged SAAB engine and good performance was obtained. This work has resulted in the paper [21].

5.4 Enhancement of Process Control Languages

Project Description and Goal The languages used for programming process control equipment has historically been vendor specific products. Recently, a standard for such languages have been agreed upon (IEC 1131-3), based on existing languages. Although defined as a standard, the languages are not in their final state — there are still details that are ill-defined, missing or contradictory. The purpose of this project is to:

1. to investigate the process control languages specified in the standard IEC 1131 regarding usability in an industrial process control and monitoring system, proposing extensions where appropriate,
2. to refine the techniques for restart of production equipment after a break down and subsequent repair, techniques that has been developed at LiTH, and to evaluate its usability in an IEC 1131-3 based process control system

Project Results

The results of the project are:

1. presentation of the article [18].
2. hosting an ISIS symposia: "Symposium on Process Control Languages", Linköping University, Nov. 28 1996.
3. the first version of a prototype implementation of the analysis algorithm completed. This version handles the single process case. The theory behind the implementation does handle the multi process case.
4. a thoroughly investigated issue list of problems and potential remedies.
5. knowledge transfer on various topics related to the project such as real-time scheduling theory and state space exploration techniques.

A final project report describing the issue list with remedies and a proposal of how to extend parts of the standard to support the analysis technique is under preparation.

5.5 Verification Automation in Software Development

This project was carried out in cooperation between ABB Industrial Systems, Västerås, and the Real-Time Systems Laboratory, Linköpings Universitet.

A significant part of the value in the process control systems developed by ABB Industrial Systems is in the embedded software. Errors in this software can lead to expensive production stops, or incidents with possible personal injuries. Hence correct software in the delivered systems is important. The general goal of the project was to develop practical means for increasing confidence in software correctness. Therefore, COMPASS, a comprehensible assertion method, has been developed. The method enables for the automatic generation of relevant, focused questions to be asked during code inspection.

All activities have been conducted in close cooperation between ABB ISY and RTSLAB. The method has been documented in a number of reports and examples by Tim Heyer and Staffan Bonnier. A prototype tool that supports the code inspection process according to the COMPASS approach has been developed and presented to ABB ISY. ABB ISY has provided the examples, performed their own case studies and reviewed the reports from RTSLAB. Project meetings have been held in Västerås and Linköping alternatively. Two other activities at ABB ISY are related to the project and are added to the ABB ISY effort in the project: The code review project at ABB ISY and the JAVA OMF project at ABB ISY. Moreover, Tim Heyer spent several days at ABB ISY in order to study ABB's software development process, in particular the code inspection process.

Two internal reports have been written, containing a description of the restrictions to the programming language C for a safe use of the method and a description of the language of assertions. Moreover, the paper [10] gives an overview of the method. The report "Advances in the Comprehensible Assertion Method" by Tim Heyer and Staffan Bonnier has been presented at SNART'97. It clarifies and refines the prerequisites for a smooth application of the COMPASS method. Furthermore, the licentiate thesis of Tim Heyer is going to present the COMPASS method in detail.

It is intended to evaluate the COMPASS method further. The experience so far has been promising. ABB Industrial Systems has stated that, even though it is to early for a final evaluation, it seems apparent that "COMPASS is a simplification compared to traditional methods". To be able to further evaluate the COMPASS approach, it is planned to develop a new extended inspection tool. This will to be done in projects involving MSc students.

The COMPASS method is concerned with the development and verification of code. However, a large portion of those mistakes which eventually lead to erroneous system behavior have their root causes in earlier phases of the development process. Therefore, it is planned to study whether the ideas of COMPASS may be applied to higher level designs. The method to be developed should help in avoiding or detecting several types of errors which today survive until testing is commenced (or later) and it should be possible to smoothly integrate the method into a typical industrial development process of today.

5.6 Integrity Monitoring of Integrated Navigation Systems

Background In civil aviation a new philosophy for flight safety and traffic management is under development. The goal is to enable an expected increase in air traffic density by reducing aircraft separation. The accuracy of the position estimate determined by the navigation system in each aircraft determines this separation. A necessary component to achieve this goal is a monitor that continuously supervises the navigation solution integrity, *i.e.* the trust that can be placed on the estimated position. Integrity monitoring is important in military applications as well.

Project results The main results are summarized in Jan Palmqvist's thesis [3]:

- a survey on navigation systems used in todays aviation applications,
- a survey on fault detection in general,
- a survey on fault detection used for integrity monitoring,
- new tailored fault detection algorithms for navigation systems based on inertial navigation systems (INS) and global navigation satellite systems (GNSS).

The latter method is based on the *Generalized Likelihood Ratio* (GLR) test, and is reported in [24] and [26]. A particular problem here, specific for navigation applications, is to tune the test to get an extremely low false alarm rate. A new approach to this problem is presented in [15].

Jan Palmqvist left LiTH shortly after defending his licentiate thesis and is since then head of the navigation department at SAAB Military Aircraft. In this capacity he continues the navigation activities within ISIS.

5.7 Sensor Fusion

Project Description and Goals Sensor fusion means that information from different sensors, typically of quite different nature, are merged to provide a better basis for decision-making. Sensor fusion can thus mean very different things in different applications. Here we have focused on navigation applications, where inertial navigation information has been merged with information from map data bases. In this application an aircraft position is autonomously determined by fusing measurements from an inertial navigation system, a digital map and a radar altimeter. By measuring the terrain height variations along the aircraft flight-path and comparing these with a digital terrain map, a position estimate of the aircraft is obtained. The comparison between the map and the measurements is a nonlinear estimation problem where unconventional and conceptually different sources of information are fused together. Research as been focused on finding a reliable and effective algorithm for this position determination. The goals have been both to obtain an efficient algorithm for this problem, and also to provide a foundation for future work on more general data and sensor fusion problems.

Results During this work, close contact has been established both with Saab Dynamics and Saab Military Aircraft. A full-scale commercial implementation of a company secret solution has been developed at Saab during a period of two decades. Their expertise in this application field has proved extremely useful when developing and testing new ideas.

An effective algorithm solving the terrain-aided navigation problem has been developed and implemented. Simulation tests comparing the newly developed method with the full-scale implementation at Saab shows outstanding performance of the new method, both concerning the speed of convergence of the algorithm and the steady state estimation accuracy. The superior performance is obtained at a fairly low computational cost which allows for online implementation.

Furthermore, the terrain-aided navigation problem has been analyzed and fundamental bounds on the achievable performance have been derived. The implemented method developed in this work has been shown to meet these bounds in extensive simulation evaluations. The bounds have also been used to derive information maps which can be used to support mission planning.

The results of the work are presented in detail in the licentiate thesis [1]. Part of the results have also appeared as conference papers [8, 9] and as technical reports [27, 28].

5.8 Supervision and Control of Industrial Robots

Project Description and Goals. This is an application-driven project, whose goal is to provide useful new enhancements of industrial robot systems. The project has two foci: (1) Iterative learning control, where techniques are developed to improve the accuracy of the robot's positioning and to overcome friction and other changes that deteriorate the behavior over time. (2) The other focus is to develop a user-friendly diagnosis system that quickly can tell why the robot has made an unplanned stop. The latter project has just started. The experiments in the robots are carried out both at ABB Robotics and at the installation at LiTH.

Iterative Learning Control: Methods and Results Iterative Learning Control (ILC) is a method that can be applied when the object to be controlled operates in a repetitive mode. The same movement is carried out repeatedly and the aim of ILC is to generate a control input that handles the systematic error in each cycle. In this work the aim is to use ILC in combination with the conventional control system.

The ILC method has been studied theoretically and in simulations, and this has resulted in one technical report and three conference papers. See [30], [13], [14] and [25].

In [30] a basic introduction to ILC is given and some of the fundamental problems concerning convergence, robustness and disturbance sensitivity are discussed. In [13] and [25] the focus is on the choice of design filters in the ILC algorithm and how this choice affects the robustness against unmodeled dynamics. Furthermore it is studied how the presence of nonlinearities influences the properties of the ILC algorithm. In [14] the sensitivity to load and measurement disturbances is considered, and it is discussed how the design filters can be chosen to reduce the influence of the disturbances.

An industrial robot of type ABB IRB 1400 has been installed at LiTH. A software interface between the robot control system S4C and Matlab has been developed. Using this interface it is possible to record a large number of different signals from the robot and also apply external signals at various positions in the control system. Using this interface it is possible to test and evaluate the iterative learning control algorithms that previously have been tested in simulations. Using the interface it is also possible to carry out identification experiments on the real robot concerning, for example, friction and flexibilities.

Two master theses with connection to the project have been carried out. The first master thesis, [29], deals with friction identification and two different methods for friction identification are compared. In the second thesis, [33], identification of resonance frequencies in a flexible servo is studied. A third master thesis is in its final phase, and in this work the applicability of an iterative method for tuning of regulator parameters is evaluated on a robot problem.

Diagnosis for Industrial Robots The problem studied in a recently started subproject can be summarized as: Why did the robot stop?

The conditions are that the robot is in operation, i.e., the installation phase is over, and the operators are fairly unexperienced with the robot system. An observation in this context is that also to handle simple faults automatically is of great value, it helps the unexperienced operators and frees the experienced.

When an industrial robot that is part of a manufacturing process stops due to a fault, it is of course of vital importance to locate the fault as fast as possible to get the system running again. The problem often is that when a fault occurs, for example an IO-board stops working or a contact is loose, a large number of error and status messages are generated, in part due to interactions of the robot subsystems. If you are not an experienced user with good knowledge of the internal structure and operation of the system, it can be hard to determine the basic fault. The system is also highly configurable, which makes the problem significantly harder.

The long term goal of the project is an implemented diagnosis system, for example running on a PC, that automatically isolates the basic fault and presents it to the user, using information available directly from the robot system and a formal model. This diagnosis system is desired to be as general as possible, so that it can be easily extended to, e.g., comprise the equipment the robot handles or a whole production cell or line.

We have so far mainly been working on an approach where a fault can be seen as a broken information chain. This approach can probably be used for diagnosis in many other areas than robotics.

5.9 Signal Interpretation and Control in Combustion Engines

Project Description This project is carried out in cooperation with MECEL AB and SAAB Automobile AB, and the aim is to study and develop methods for improving the performance of signal interpretation and control in combustion engines. The focus is on dynamic effects and model based methods.

Project Goal Today's engines are controlled by empirically obtained and fixed engine maps. Further, if not using measurements internally in the cylinder like the ionization current, engines are basically controlled without direct feedback from the combustion itself. This will not be sufficient in future engines if high efficiency and low emissions are to be obtained. Possible legal requirements on high functionality in 100000 miles will even more increase the need for better methods.

The aim of the project is to study and develop methods for improving the performance, with use of signal interpretation and handling of dynamic effects, in combustion engines. Control that handles varying conditions is, together with ionization current interpretation, an important issue. Ignition timing control is to be studied using ionization current interpretation to obtain cylinder pressure characteristics. Model based closed-loop control in connection with ionization current interpretation should be demonstrated.

A number of methods are relevant to study within the project goal to handle dynamic effects. These methods include for example sensor fusion, adaptive dynamic models, and improved engine mapping. There will be a need to study control principles , e.g. how to choose set points, and there is also a connection to diagnosis and supervision.

Milestone Closed-loop control of ignition timing under varying conditions has been developed. This is a new result and not been demonstrated by others except when using (expensive) extra sensors. We aim at using existing sensors in combination with signal interpretation.

Project Results Lars Eriksson's Licentiate thesis, [5] presents the signal interpretation schemes that are used to extract information from the ionization current signal. Furthermore it includes a demonstration of closed-loop spark-advance control using only information obtained from the spark plug.

Control handling disturbances is crucial for the spark advance controller. Closed-loop experiments, with water injected into the engine intake system as a combustion disturbance, demonstrated that the controller based on the ionization current successfully maintains the spark advance at its optimal position. Under normal conditions this scheme also resulted in an increased engine efficiency of about 1-3%. The results are presented in [12]. By this experiment, with closed-loop spark-advance control during varying conditions for the spark advance controller, a first full scale demonstration within the stated project milestone has been reached.

Related work To gain an understanding of the fundamental processes in the combustion that governs the engine efficiency, an investigation of combustion and heat-release models was started. Results from the study was collected [11]. This relates to the ISIS project in gaining knowledge of how the spark advance influences pressure development and thus how the spark advance should be positioned for optimal engine efficiency.

Two master thesis projects in the areas of engine control and simulation have been initiated and supervised by Lars Eriksson, they were both completed during 1997. In one project a method, for on-line updating of the maps that are present in all engine controllers, was evaluated and tested. The other project developed a real-time platform that can be used to simulate and control spark ignited engines.

6 Administrative Information

6.1 Cooperation between Industry and Academia

The cooperation between the industrial and the university groups is of course at the heart of the center's activity. We have worked with several different ways to strengthen the links.

Projects Within the projects there are clearly intense contacts. They have been commented upon above in connection with the individual projects.

TKG-groups For each company we have created a contact group (TKG-group, "teknikkontaktgrupp") comprising 2-3 people from university and 2-3 people from the company. The groups meet about 6 times a year, typically at the company, to discuss technical questions and problems within the ISIS area. These activities are not related to the projects and aim both at finding new projects and at disseminating information in more general terms.

Half-day workshops In addition to the regular semi-weekly ISIS-seminars we have also arranged half-day workshops on specific topics. For these we have aimed at (and achieved) about 50 % industrial participation, both among speakers and attendees. The following half-day workshops were organized during phase 1

- March 18, 1996: Detection and Diagnosis
- September 10, 1996: Hybrid Systems
- November 21, 1996: Yearly ISIS Workshop
- November 28, 1996: Programmable logic controllers
- March 20, 1997: Engine Control and Diagnosis
- April 17, 1997: Databases
- October 23, 1997: Yearly ISIS Workshop

6.2 Management Issues

The management structure of ISIS contains the following levels:

- *The Board*. Takes decisions about budget, which projects to run, and general policy questions. It meets 2-3 times per year and consists of
  - Ulf Rehme, SAAB AB (chairman)
  - Staffan Ahlinder, ABB Industrial Systems
  - Hans Alberg, Ericsson Development

- Jan Nytomt, MECEL
  - Erik Sandewall, LiTH

- *The Reference Group.* It consists of the team leaders at LiTH and and one representative from each company. It is appointed by the board and serves as the main information channel between the companies, the board and the university. All major decisions about ISIS should be approved by the reference group, and it also serves as an advisory panel for the Board. The Reference Group receives all Board documents. It meets twice a year Currently, it comprises the following persons
  - Staffan Ahlinder, ABB Industrial Systems
  - Hans Alberg, Ericsson
  - Torgny Brogårdh, ABB Robotics
  - Jan Dellrud, SAAB Automobile
  - Inger Klein, LiTH Automatic Control
  - Lennart Ljung, ISIS manager
  - Lars Nielsen, LiTH Vehicular Systems
  - Jan Nytomt, MECEL
  - Helge Persson, SAAB Dynamics
  - Tore Risch, LiTH EDSLAB
  - Erik Sandewall, LiTH RKLLAB
  - Karl-Einar Sjödin, NUTEK
  - Anders Törne, LiTH RTSLAB
  - Jan Westlund, SAAB MA
  - Ulla Salaneck, LiTH, ISIS Secretary
- *The group of LiTH team leaders.* This is an informal group that meets once a month to monitor the projects and prepare issues for the Reference Group and the Board. It consists of the LiTH part of the Reference group.
- *Project management.* Each of the projects have also their own management structure. See the list of projects in Section 2.
- *Seminar Organizer.* Inger Klein has been responsible for organizing the bi-weekly seminar series, the half-day workshops and the annual ISIS workshop.
- *The ISIS Manager*, Lennart Ljung, is together with *the ISIS Secretary*, Ulla Salaneck, responsible for the day-to-day operation, preparing issues for the Reference Group and the Board, monitoring the projects, budget, economy, and other ISIS operations, information and PR activities (including the ISIS Web-site), and reporting to NUTEK and the Board.

Project #	Project Name
1	Real-time databases for telecom
2	Databases for integrated navigation systems
3	Diagnosis for car engines
4	Enhancement of process control languages
5	Verification automation in software development
6	Integrity monitoring of navigation systems
7	Sensor fusion
8	Supervision and control of industrial robots
9	Signal interpretation and control in combustion engines

Table 1: List of Projects

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Licentiate Theses, Completed entirely within ISIS

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[2] Lin Ling: *A Value-based Indexing Technique For Time Sequences*, Licentiate Thesis No 597, Linköping University, ISBN 91-7871-888-0.

[3] J. Palmqvist. *On Integrity Monitoring of Integrated Navigation Systems.* Licentiate thesis LIU-TEK-LIC-1997:01, Department of Electrical Engineering, Linköping University, Linköping, Sweden, February 1997.

[4] M. Nyberg. *Model Based Diagnosis with Application to Automotive Engines.* Licentiate thesis LIU-TEK-LIC-1997:637, Department of Electrical Engineering, Linköping University, Linköping, Sweden, 1997.

Licentiate Thesis, Partly completed within ISIS

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