VINNOVA's Competence Center **ISIS**
Information **S**ystems for **I**ndustrial Control and **S**upervision
Annual Report 2004 (Public Version)

Lennart Ljung

1 Sammanfattning

År 2004 har varit det första året av Fas IV. Under året har fördjupningen och utvidgningen av samarbetet fortsatt mellan de deltagande företagen och forskargrupperna vid LiTH (Linköpings Tekniska Högskola) och har resulterat i industriellt relevanta forskningsresultat.

Huvudaktiviteten inom ISIS är *forskningsprojekten.* Projekten har valts ut för att vara av central betydelse för företagen. Att balansera uppgifterna att ligga vid forskningsfronten, att leverera avhandlingar av hög kvalitet, samtidigt som att dessa resultat skall vara direkt användbara och intressanta för deltagarföretagen är kanske den främsta utmaningen inom kompetenscentret. Vi anser att vi varit framgångsrika i att uppnå denna balans för ISIS.

Som några sammanfattande punkter kan nämnas

- Fyra ISIS-doktorander avlade licentiat-examen:
  - Jonas Gillberg
  - Thomas Gustafsson
  - Marcus Klein
  - Erik Wernholt
- Företagen ABB Automation Systems, ABB Automation Products och ABB Robotic Products har sammanförts i ett nytt företag *ABB Automation Technologies AB* som formellt är ny ISIS-partner.
- Mikael Norrlöf och Torgny Brogårdh gav en presentation av robotiksamarbetet inom ISIS vid den årliga KompetensCentrumDagen i Stockholm, i år i samarbete med RIFO (Sällskapet Riksdagsmän och Forskare).

2 Summary

The year 2004 has been the first year of Phase IV. The year has been characterized by continued strategy work.

Work has progressed with further broadened collaboration between the participating companies and the research groups at LiTH (Linköpings Tekniska Högskola) and production of industrially relevant research results.

The main activities within ISIS are 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.

In summary we would like to mention:

- Four ISIS-students completed their Tekn.Lic.-degrees:
  - Jonas Gillberg
  - Thomas Gustafsson
  - Marcus Klein
  - Erik Wernholt
- The companies ABB Automation Systems, ABB Automation Products och ABB Robotic Products have merged to a new company *ABB Automation Technologies AB*, which from a formal point of view is a new ISIS-partner
- Mikael Norrlöf and Torgny Brogårdh gave a presentation of the robotics work in ISIS at the yearly Competence Center Day in Stockholm, this year in cooperation with RIFO (The association for members of Parliament and Researchers).

3 Current ISIS Projects

The following projects have been undertaken during the year:

- Data Bases for Control, Modeling and Simulation
  - Embedded Real-time Databases for Engine Control Jörgen Hansson, Thomas Gustafsson
- Diagnosis, Supervision and Safety
  - Diagnosis and Supervision for Vehicle Functions
    Lars Nielsen, Erik Frisk, Marcus Klein, Lars Eriksson
  - Fault Isolation in Object Oriented Control Systems
    Ulf Nilsson, Inger Klein, Dan Lawesson
  - Detection and Diagnosis in Control Systems
    Lennart Ljung, Inger Klein, Fredrik Gustafsson, Anna Hagenblad, Mattias Krysander
- Techniques for Developing Integrated Control and Information Systems
  - Resource Management in Wireless Communications Systems
    Fredrik Gustafsson, Fredrik Gunnarsson, Erik Geijer Lundin, Frida Gunnarsson
- Methods for Synthesis of Control and Supervision Functions

  - Supervision and Control of Industrial Robots
    Svante Gunnarsson, Mikael Norrlöf, Erik Wernholt
  - Model Predictive Control for Systems Including Binary Variables
    Anders Hansson, Torkel Glad, Daniel Axehill

- Signal Processing in Integrated Control and Supervision Systems
  - Navigation Systems
    Fredrik Gustafsson, Gustaf Hendeby
  - Signal Interpretation and Control in Combustion Engines
    Lars Eriksson, Per Andersson
  - Sensor Fusion
    Fredrik Gustafsson, Rickard Karlsson, Jonas Gillberg

4 Administrative Information

4.1 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 are 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 4 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.

ISIS workshop

- ISIS Yearly Workshop took place on November 4, 2004 with around 50 participants. The workshop had presentations by
  - *Lennart Ljung*: A proposal for a Vinn Excellence Center
  - *Mikael Norrlöf*: Towards improved performance for industrial robots
  - *Albert Benveniste*: Challenges and techniques for the observation and control of large distributed systems
  - *Rickard Karlsson*: Particle filtering in practice – Positioning and tracking applications
  - *Richard Backman*: Challenges for engine control
  - *John Baras*: Information centric systems engineering and integration: Math and Science foundations.

  The Workshop 2004 also included a project and poster exhibition giving details of all the ongoing projects.

4.2 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 three times per year. The Board now consists of
  - Torgny Brogårdh, ABB Automation Technologies (chairman)
  - Joakim Ed, SAAB Automobile
  - Ulf Persson, ABB Automation Systems
  - Urban Forssell, NIRA Dynamics AB
  - Anders Göras, MECEL
  - Anders Skeppstedt, SAAB Bofors Dynamics
  - Ulf Moberg, ABB Automation Products
  - Per Erik Modén, ABB Corporate Research
  - Jan Palmqvist, SAAB AB
  - Gunnar Bark, Ericsson AB
- *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 once a year. In 2004, it consisted of the following persons
  - Petru Eles, LiTH, ESLAB
  - Lars Eriksson, LiTH, Vehicular Systems
  - Torkel Glad, LiTH, Automatic Control
  - Svante Gunnarsson, LiTH, Automatic Control
  - Fredrik Gustafsson, LiTH, Automatic Control
  - Anders Hansson, LiTH, Automatic Control
  - Jörgen Hansson, LiTH, RTSLAB
  - Inger Klein, LiTH, Automatic Control
  - Lennart Ljung, ISIS Manager
  - Lars Nielsen, LiTH, Vehicular Systems
  - Ulf Nilsson, LiTH, TCSLAB
  - Torbjörn Fängström, VINNOVA
  - 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 also has its own management structure. See the list of projects in Section 2.
- *Seminar Organizer.* Inger Klein has been responsible for organizing the seminar series and the half-day workshops.
- *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 VINNOVA and the Board.
- *The Scientific Advisory Board:* Professor J. S. Baras, University of Maryland, USA, Professor E. Clarke, Carnegie-Mellon University, Pittsburg, USA, Professor A. Benveniste, IRISA, Rennes, France, Professor B. Neumann, Universtität Hamburg and Professor E. Sandewall, LiTH.

4.3 Agreements

In addition to the general agreement between VINNOVA, LiTH, and the companies, the individual researchers at LiTH, working with ISIS, have signed an agreement with Linköping University to follow the clauses of the main agreement. The duration of these individual agreements follows the main one. These agreements are being complemented to be up to date to cover all currently involved researchers.

5 Plans Beyond the Year 2005

The state and fate of ISIS beyond the first 10 year period, which ends 2005 has been debated within our advisory board, within the board, and with the evaluators for Phase III. It has also been brought up informally within the faculty. There is a clear consensus that it will not be possible to maintain a good operation of ISIS without external (i.e. external to both the university and the participating companies) financial support. The University most likely will not have resources to fill in for the current external support. While, in principle, the companies could increase their cash contributions substantially, this cannot happen with a maintained balance between scientific excellence and industrial needs. The conclusion is thus that ISIS will have to investigate routes for continued external support.

We have during 2004 submitted a preproposal to VINNOVA for a VINN Excellence Center OSIRIS. This should not be seen as a continuation of ISIS. It however builds on the experiences from ISIS. It has quite a wide spectrum of potential industrial parters, which contains the current ISIS partners.

6 Project Reports

Project 1: Embedded Real-time Databases for Engine Control

Overview

It has been identified by the car industry that there is a strong need for increased tool support in order to handle the increasing functionality and complexity for the next generation of engine control systems. This need origins from increased law regulations and diagnosis requirements for handling faults, with the implication that the amount of data managed by the engine control system has increased drastically, as well as the complexity of the engine control system itself. Databases have been envisioned as one tool to improve the situation This research focuses on incorporation of database and transaction support in engine control system for automobiles, with the vision that all data transactions, including extremely fast and critical transactions in the control loop as well as transactions outside the control, e.g., for diagnosis, should be carried out by a real-time database that is integrated with the engine control system. Emphasis is given to software architectural considerations of the database and the engine control system, and models for transaction execution under temporal constraints on data and transactions (primarily expressed as absolute validity intervals, relative validity intervals, deadlines etc), where the workload consists of multi-class transactions requiring differentiated processing due to transaction criticality and real-time performance requirements. Further, methods for event-driven control of processes to be activated have been raised as an issue.

The impact of successful deployment of a database in this type of system is high. First, by using central repository for data management, one can avoid unnecessary storing of data at the different processes, which enhances software maintainability and fosters better software evolution due to the simpler structure and the removal of data subscription models. Second, this also simplifies the programmers' tasks since large parts of synchronization can be performed by the database, and that time constraints, such as data validity, can be enforced by the database. Third, but not the least, the database can manage limp-home-values, decreasing the complexity and the cost of sensors in the engine.

Developments under 2004

During 2004 a general multi-version concurrency control with similarity (MVTO-S), i.e., validity bounds are used, has been developed. This algorithm is a combination of an updating algorithm with relevance check, e.g., ODTB, and a concurrency control algorithm using several versions of data items. MVTO-S has the properties of guaranteeing that transactions are presented an up-to-date view of the database from the time when the transaction was started. Three implementations of MVTO-S have been evaluated using the database developed in track 2. These evaluations are compared to well-established single-version concurrency control algorithms not using similarity. The implementations of MVTO-S perform better than HP2PL and OCC-BC and are also able to guarantee the up-to-date snapshots. Also, Thomas Gustafsson successfully completed his Licentiate thesis/degree.

People during 2004

- Jörgen Hansson (contact person), jorha@ida.liu.se
- Thomas Gustafsson, doctoral student, thogu@ida.liu.se
- Hugo Hallqvist, final year project student.

Industrial Partners

- Saab Automobile AB, Södertälje.
- Mecel AB Åmål, contact person Anders Göras (anders.goras@mecel.se)

In addition, we have technical support from Arcticus, contact person Kurt-Lennart Lundbäck.

Project 2: Diagnosis and Supervision for Vehicle Functions

Project Description

This ISIS project is carried out in cooperation with SAAB Automobile AB and MECEL AB, and the aim is to study and develop methods for improving the performance of function supervision and on-board diagnostics systems. The focus is on problems relevant for engine emissions, performance and drive-ability. The method that will be considered is model based diagnosis.

Lars Nielsen is project coordinator and the responsible researchers are Erik Frisk, Marcus Klein and Lars Eriksson, all at the Division of Vehicular Systems.

Project 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 function supervision for drivability, repairability, availability and vehicle protection. The techniques used in production vehicles were earlier 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.

The *goal* is to increase the capability of function supervision and diagnosis to function over larger parts of typical driving cycles. In that way, for example, requirements on diagnosis during idle is relaxed and overall performance can therefore be increased.

One way to increase the performance of the engine diagnosis system is to use model based diagnosis in which more process knowledge is used in the form of a mathematical process model. This is one important direction of research.

Further, diagnosis methods for new types of engines is important to consider. In our research lab, a new engine with variable compression has been installed. This new type of engine opens up new issues both in control and in diagnosis.

Project Results 2004

During the year Marcus Klein presented his Licentiate thesis [3] together with results concerning modeling, methods and applications of cylinder pressure data. New diagnosis issues concerning a new engine type with variable compression ratio have been addressed [30, 3, 31, 9], where the methodological aspect has been in focus. A new cylinder pressure model which increases the modeling accuracy by a factor 15 in the mean compared to a commonly used model has been developed [29, 3, 32]. This model is at the same time almost as computationally efficient as the previously proposed one. All these issues also couple to project 10: Signal interpretation and control in combustion engines.

Project 3: Fault Isolation in Object Oriented Control Systems

This is a joint project between the Division of Automatic Control and the Theoretical Computer Science Laboratory in cooperation with ABB Automation Technologies. The current project members are Inger Klein, from the Division of Automatic Control, and from the Theoretical Computer Science Laboratory: Dan Lawesson and Ulf Nilsson. Magnus Larsson has been the industrial contact after completing his Ph.D. thesis within the scope of the project in 1999 and moving to ABB.

The aim of the project is to study and develop methods for fault handling in object oriented control systems, in particular for industrial robots. The goal is to develop an automatic diagnosis system that can guide an operator in isolating the main cause why an industrial robot has made an unplanned stop. Our primary concern is a situation where we have an operational system which is normally running without direct supervision. Moreover, operators or service personnel summoned when the system halts are fairly unexperienced with the system. The basic philosophy here is that improvement of the handling and reporting of faults, even simple ones, can be of great help; it helps unexperienced operators and unloads experienced. The fault handling procedure described here can also be used as a design tool when designing error messages.

We propose a model-based approach to fault isolation. The faults considered are hardware faults, but we assume that they are either modeled explicitly (in the same framework as the software) or that malfunctioning hardware is reflected in failing software services. The software has an object oriented architecture which makes fault isolation especially hard, since object orientation relies heavily on encapsulation. This implies that software components have little knowledge about the global state of the system, and in particular whether error reporting is going on elsewhere. This often leads to many (irrelevant) alarms when faults occur. Moreover, the alarms typically reflect the software architecture which an operator has little knowledge of.

Because of the safety-critical nature of the application, fault isolation can take place only after the system comes to a stand-still. The software has a relatively small number of concurrent threads, but this, together with the fact that safety-critical actions may have to be taken before error reporting can take place, means that the order among error messages in the central log cannot be trusted.

We have described a software tool (StateTracer) that assists an operator in isolating the cause of the failure [41]. The approach is model-based and relies on interacting finite state machines (e.g. UML state charts) modeling the behavior of software components including communication, internal events, critical events (faults) and error reporting. Hence, given an actual error log it is possible to infer what critical event that might have caused a particular log. In [41] we show how a combination of abstraction and exhaustive state traversal, so-called model checking, can be used to isolate the root cause. More recently we argue that isolation of the root cause can be greatly simplified by abstracting the system description into a single FSM that is equivalent to the original system from the fault isolation perspective [42]. The resulting FSM essentially is a table coupling all possible logs with the critical event (or events) that caused them. Hence fault isolation reduces simply to table lookup. The resulting automaton can be used not only to isolate faults in a specific scenario but can also be used statically to determine e.g. diagnosability, or if the system contains superfluous error messages.

Our abstraction consists of replacing pairs of components by a new component which behaves as the pair—both in terms of interaction with the context and from the fault isolation perspective—but where all other irrelevant behavior is discarded. The merging is iterated until the system consists of a single component which is identical to the original system from the fault isolation perspective. The control system that we consider has relatively few threads of execution, and has a stable and rather sparse topology. However, state space explosion *is* an issue and the approach is worst-case exponential. But in practice the algorithm is often feasible if the selection of pairs is done carefully as illustrated in the experimental evaluation of our algorithm.

Project 4: Detection and Diagnosis in Control Systems

Structural analysis for design and analysis of diagnosis systems

The overall goal is to find a methodology for designing diagnosis system for individually designed pulp and paper applications. Three challenges of the task are model complexity, complicated sub-models and uniqueness of the plants. These systems have hundreds of equations. Even small parts of the system have complicated mathematical descriptions. Each plant is unique, e.g. it is necessary to make a complete new diagnosis system for each plant.

A good diagnosis system has to be designed parallel to the plant design, and not afterwards. An example is to choose useful sensors for diagnosis. Since each plant has to be analyzed individually, the analysis has to be done fast and automatically to be affordable. Early design of the diagnosis system means that this method must be capable of handling incomplete models.

Structural analysis is a good approach to meet the above mentioned demands. The method only requires the information of which variables that are included in each equation, i.e. the structure of the model. The structural model can be constructed from equations or from reasoning.

Incorporating diagnosis design into process design

The first part of the project has examined a part of a paper mill with given sensors and structure. An approach for designing diagnosis systems utilizing the structure of the system is presented. It is shown that structural analyses predict fault detection and isolation under some natural assumptions.

During the year 2004 we have extended the structural method of predicting diagnosis capability for a fixed sensor configuration to find suitable sensor configurations given detectability and isolability requirements. An algorithm and a Matlab implementation of this algorithm has been developed. The algorithm has been used to study the diagnosis potential and suggesting sensor configuration in the fuel system of an Unmanned Aerial Vehicle (UAV) [63].

Designing diagnosis systems utilizing structural analysis

When designing model-based fault-diagnosis systems, using the principle of consistency based diagnosis, a crucial step is the conflict recognition. Conflict recognition can be achieved by using pre-computed analytical redundancy relations. With properly chosen analytical redundancy relations, different subsets of analytical redundancy relations are sensitive to different subsets of faults. In this way isolation between different faults can be achieved.

The systems considered are assumed to be modeled by a set of nonlinear and linear differential-algebraic equations. To find analytical redundancy relations by directly manipulating these equations is a computationally complex task, especially for large and nonlinear systems. To reduce the computational complexity of deriving consistency relations, we propose a two-step approach. In the first step, the system is analyzed structurally to find over-determined sub-models. Each of these sub-models are then in the second step transformed to analytical redundancy relations. The benefit with this two-step approach is that the sub-models obtained are typically much smaller than the whole model, and therefore the computational complexity of deriving analytical redundancy relations from each sub-model is substantially lower compared to directly manipulating the whole model.

Finding these sub-models is a time-consuming and demanding task, hence it is preferable if as much as possible of this process can be automated. A structural algorithm for finding these sub-models has been developed. Instead of directly manipulating the equations themselves, the proposed algorithm only deals with the structural information contained in the model. A method for transforming simulink models into analytical equations and structural models has been developed. As a way of increasing the diagnostic performance for a model based diagnostic system, information about different faults, called fault models, can be included in the model. For simulink models, there is no direct way in which this can be performed. However a systematic inclusion of fault models is proposed. The correctness of the algorithms are proved and the algorithms have been applied, with supreme results, to a truck engine model [62].

Finding analytical redundancy relations in over-determined differential algebraic models

A common basis for design of diagnosis systems is to use residuals based on analytical redundancy. The over-determined sub-models computed by the structural algorithm provide analytical redundancy and by using minimal over-determined sub-models, sensitivity to few faults is obtained.

For many over-determined differential algebraic models, it is difficult to compute an analytical redundancy relation. It is shown how the differential algebraic problem of deriving an analytical redundancy relation is reduced to an algebraic problem. This is done by differentiating equations, a new set is formed, that is an over-determined static algebraic system if derivatives of unknown signals are considered as separate independent variables. It is desirable to differentiate the equations as few times as possible and it has been shown that there exists a unique minimally differentiated over-determined system. This work will be published in 2005.

Project 6: Resource Management in Wireless Communications Systems[1]

Resource Management Algorithms: Background

The third generation cellular radio systems is in many aspects conceptually different from the first and second generations. In these previous generations, resource management was to a large extent concentrated on channel allocation, where users share a fixed resource such as channels similar to classic work by Erlang et al. In the third generation (as well as in some upgraded second generation systems), the available resource is not fixed, but flexible and depend critically on the network deployment. The wireless communication system comprises many algorithms which have to be implemented in a distributed fashion but mutually affect each other. Also the information is distributed, and full observability of the system behavior is almost always not possible. Therefore, careful design and analysis of the various algorithms is crucial.

This project is carried out by Division of Communication Systems and Division of Automatic Control in cooperation with Ericsson Research. The aim is to apply methods from control theory and signal processing to algorithms on different layers in wireless communications systems.

One instructive approach is to separate the resource management in two segments:

- Radio resource management. This segment focuses on the radio access network to enable efficient transport of data from transmitters to receivers. Aspects, such as efficiency, feasibility, stability, fairness etc are central.

- Data network control. The data over the links is not continuous, and its flow depend on the behavior of the core network run by the operator, and of other connected networks, such as the Internet. The data flow depends on both end-to-end transport protocols and on flow control mechanisms in nodes.

The activities are concentrated to:

- Identification and modeling of different network components and layers, based on control theory methodology. Primarily, the algorithms can be

[1] There is no project 5 this year. The numbering has been kept consistent with that of earlier years

separated with respect to time constants, input and output signals, and physical location, to identify potential conflicts.

- Development of coordinating radio network algorithms. This also includes studying cross-couplings and conflicts between existing algorithms, as well as investigating robustness of distributed algorithms.
- Model data flow control to better relate to radio network properties.

Project Overview

The projects will be described using a top down approach, from flow control of data packets sent over the wireless links, via radio interface admission control of new users and finally to control of individual transmitter powers. The overall situation is depicted in Figure 1.

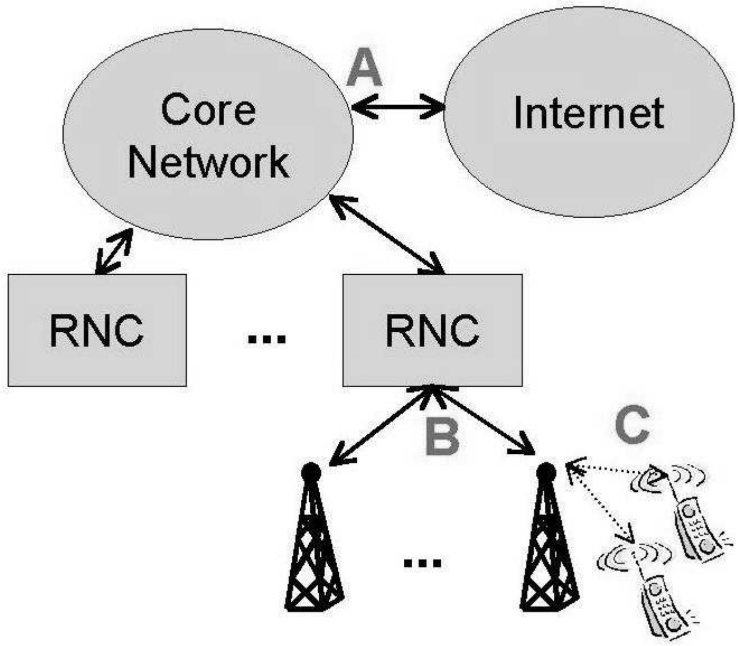

Figure 1: Radio network connected to a core network and the Internet

Data flow control primarily makes impacts on the core network and other connected networks, but also relates to radio network properties. Uplink load estimation and control addresses the situations at the base station, which is monitored in the RNC (Radio Network Controller). Control of individual transmitter powers mainly deals with the situation between the base station and the mobile situation.

Data Network Flow Control

Many people consider 3G as the technology that makes Internet generally available to mobile users. This means that the fields of telecommunications and data communications will overlap to a greater extent than before. While the paradigm in data communications is flexibility, the key word within telecommunications is efficiency of the wireless link. Therefore, some flow control mechanisms used of wired Internet causes problems when used directly over wireless links. Furthermore, these flow control mechanisms were designed assuming different

traffic characteristics than prevalent today. The field of data network control is "hot" within academia, and much effort is spent on modeling the control protocols and the queues of the switches and routers. The main idea with the project is to combine core knowledge in control theory and in telecommunications resource management, to form better understanding as well as better and more relevant models for the observed phenomena. One distinguishing property of the flow control problems is that new information becomes available upon packet arrivals, which means that the input signals are non-uniformly sampled in time. To better control queue lengths etc, a model of the observed data is instructive. In [13] frequency analysis of non-uniformly sampled data is discussed. The impact from the sampling can be seen as a frequency window applied to the continuous time Fourier transform to spread a distinct continuous time frequency over a frequency range.

In order to study the impact from modifications to queue management etc in combined fixed and wireless networks, additions to the network simulator *ns-2* has been made. The Master Thesis [60] describes recent modeling of radio resource management and investigates the impact from using too simplified models of either the fixed or the wireless part of the network. The conclusion is that in order to quantify end-to-end performance accurately, neither part can be represented by simplistic delay models.

Related to this project are also the two Master Theses [59, 61], which addresses the performance of evolved 3G systems for streaming services and in unlicensed frequency spectrum, respectively.

Uplink Load Estimation and Control in WCDMA

A prerequisite for proper behavior of radio network algorithms is that not more users than actually can be served are admitted into the system. This is of course intuitive, but with limited observability rather difficult to ensure. The situation is especially hard in the uplink communications from mobiles to the base stations, since the system has no absolute control of the transmitter powers of the mobiles. These depend in turn on the radio propagation conditions, which are subject to rapid changes. A relevant quantity is the total received power relative to the noise power, often referred to as the noise rise, NR. This can be associated to a cell load L, which is defined by

$$NR = \frac{1}{1-L}$$

As also seen in Figure 2, it is very important to operate at moderate load levels. Fluctuations at high load levels have a critical impact on the noise rise.

A high level of noise rise means that many mobiles will have insufficient transmission power to transmit data successfully at the allocated service data rate (i.e. insufficient service coverage). It is also an indication of potential instability problems in the network. The key property is *feasibility*, which means

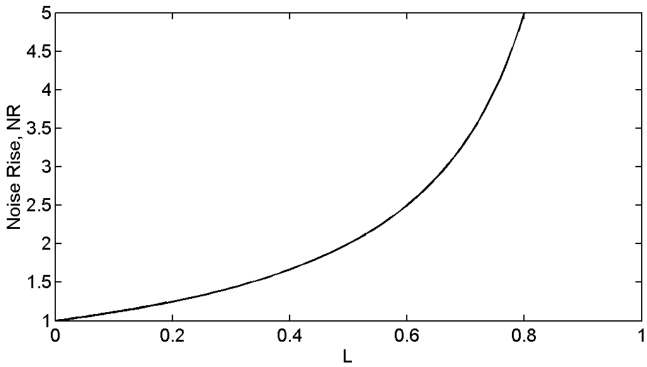

Figure 2: Relation between noise rise and load

that there exists finite transmission power levels for each uplink connection to meet the allocated service requirements. This is discussed in detail in [39, 8].

The load estimation accuracy can be improved if the channel activity is considered instead of using a full activity assumption. Some ideas relating activity estimation and load estimation are presented in [37].

Ensuring an efficient uplink communication is not only about ensuring proper admission and congestion control of potential users. There is also performance to gained by improving data transport over individual links. *Uplink Transmission Timing* [10] is a method based on statistical multiplexing of uplink usage, aiming at a certain channel activity for the individual links, and a decentralized scheduling mechanism in the mobile that aim at the target channel activity, while selecting transmission instants carefully to minimize power consumption and thereby the uplink interference contribution.

Another plausible improvement is on the receiver side. The uplink reception is interfered by all other incoming connections to the same base station - connections that are known. Similar to noise cancelling, this interference can be at least partially cancelled using advanced multi-user receivers. Some system performance aspects of interference cancellation is discussed in [36].

Transmitter Power Control

The main resource in future 3G systems such as WCDMA is power and spectrum.

Since the users share the same spectrum, power control is an important means to utilize the resources efficiently. The control of each transmitter power can be seen as distributed feedback control loops. As such, time delays, feedback bandwidth, sample rate etc. constitute fundamental limitations to the power

control performance, which most naturally are analyzed using control theory methodology [7]. Furthermore, control theory also facilitates the control design, and a compact discussion regarding the control theory aspects of power control is found in these publications.

Related Work

Some work bridges the projects. Positioning in wireless communication networks is one example where a sensor fusion approach is used to address the problem. Since non-linearities and non-Gaussian noise are present, the particle filtering framework is plausible.

Project 7: Supervision and Control of Industrial Robots

Iterative Learning Control

Iterative learning control (ILC) has been an active field of research since the mid 80's. The method uses the fact that if a systems perform the same action repeatedly and has a deterministic behavior the error will also contain a component that is repeated. By using the error from previous "iterations" of the same action the error can be reduced. The structure of the problem is shown in Figure 3 where the output of the ILC algorithm is $u_{k+1}(t)$ defined for $0 \leq t \leq t_f$. Mathematically the algorithm can be formulated as

$$u_{k+1} = Q(u_k + Le_k)$$

where u_k is an input to the controlled system and e_k is a measure of the control error. Q and L are operators that can be chosen by the user. One important aspect that has been covered in 2004 is the effect of disturbances on a system controlled with an ILC algorithm. In [6] iteration varying filters in the update equation of the ILC algorithm is covered.

Conventional robot control systems utilize measurements of the motor angles for controlling the movement of the robot, and this has been the case also in the studies of ILC. In [33] it is studied how accelerometer measurements can be used in combination with ILC in order to improve the performance. The results in [33] are based on a simple form of sensor fusion, where measurements of the motor angle are combined with measurements of the load acceleration. This idea is generalized to a three degrees-of-freedom robot in [22].

Trajectory generation

In order to obtain good performance in robot control it is essential to have good methods for representation and generation of robot trajectories. This problem has been studied for some time in the project and some new results have been obtain within the work presented in [68]. The main idea is to split the problem into a geometrical problem and a dynamical problem, and to use splines for

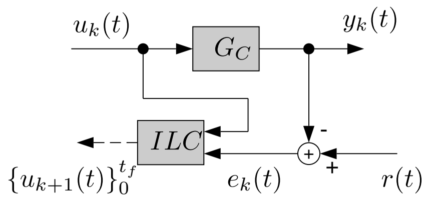

Figure 3: An example of a system controlled using ILC.

representation of the trajectories. To support the approach a Matlab toolbox has been written for generation and manipulation of trajectories.

Robot Identification

For both control and diagnosis of industrial robots it is important to have good mathematical models describing the properties of the robot. System identification of industrial robots is an essential research area within the project, and it has been studied from the following viewpoints:

- Frequency domain identification of the multivariable frequency response function (MFRF) applied to the three main axes of an industrial robot.
- Nonlinear grey-box identification of robots.
- Recursive identification of linear grey-box models.

The first area is considered in [4] and [11], and several aspects of the problem are treated. One result is an error expression characterizing the estimation error obtained when a frequency domain identification method is applied to data collected in closed loop. The theoretical expressions are compared to both simulated and measured data. An important feature of the robot application is that the measured input and output signals are affected by deterministic disturbances of very special character.

The report [4] also deals with nonlinear grey-box identification of a robot model containing nonlinear friction and mechanical flexibility with nonlinear characteristics.

The paper [5] deals with recursive identification of linear grey-box models. The recursive (on-line) parameter estimates can, in a second stage be used for diagnosis purposes.

Project 8: Model Predictive Control for Systems Including Binary Variables

Overview

Model Predictive Control (MPC) has proved to be a strong method to control large MIMO systems and has gained substantial interest in the industry, especially within the process and petrochemical fields. The main benefit is the possibility to handle constraints on various variables in the plant.

An extension to ordinary MPC is to include the ability to use binary variables as control signals and as internal variables in the model description. This extension enables both the use of binary actuators as well as more advanced model descriptions as piecewise affine (PWA) and mixed logical and dynamical (MLD) descriptions.

The central idea in MPC is to state the control problem as an optimization problem, and solve this optimization problem on-line repeatedly. When binary variables are used in MPC, the optimization problem to solve is changed from a Quadratic Program (QP) to a Mixed Integer Quadratic Program (MIQP), where the latter is known in general to be NP-hard.

As an example of linear MPC, let us consider a linear system

$$x_{k+1} = Ax_k + Bu_k \tag{1}$$

A standard MPC controller for this system is typically defined as

$$
\begin{aligned}
u_k &= u_{k|k} \\
u_{(\cdot|k)} &= \arg\min_{u_{(\cdot|k)}} J_k \\
J_k &= \sum_{j=0}^{N-1} \|x_{k+j|k}\|_Q^2 + \|u_{k+j|k}\|_R^2 \\
u &\in \mathcal{U},\, x \in \mathcal{X}
\end{aligned}
\tag{2}
$$

If $\mathcal{U}$ and $\mathcal{X}$ denotes linear constraints, the problem can be solved using a standard QP solver. When also binary variables have to be computed, an MIQP solver has to be used. Unfortunately, the computational complexity for computing binary variables is exponential. From this the fact, the need for more computationally efficient MIQP optimization routines arises.

The objective with the research is to find algorithms that improves the computational performance for MPC problems including binary variables.

The research is performed in collaboration with ABB Corporate Research.

Project 9: Navigation Systems

This project is carried out by Division of Communication Systems and Division of Automatic Control in cooperation with SAAB Bofors Dynamics and Aerospace.

Background

In the recent years activities in the navigation field have been boosting. There are and will be more and more areas where navigation becomes an important part of a system solution. So far navigation systems have been of major importance for aircraft, missiles, ships, etc., but it is now becoming used in automobiles and other smaller systems. Even in aircraft systems the advance in computer capacity has opened the possibility for a broad spectrum of applications where accurate navigation plays an important role. Typical tools today for navigation are inertial navigation systems (INS), which essentially means that acceleration and angular velocity measurements are integrated to a position. Systems that have an increasing importance are Global Navigation Satellite Systems (GNSS), e.g. the Global Positioning System (GPS), which are based on satellite information. The use of maps and terrain information (on charts or databases) has recently become a competitive component in navigation systems. Other sensors are more traditional sensors as for instance distance measuring equipment that can measure distances to stations at known locations. A good navigation system should be capable of integrating the information from different sources in an efficient and reliable way. In an aircraft application the requirements put on a navigation system varies with respect to reliability depending on what the objective is at a certain moment. One objective is a challenge from a reliability point of view - the landing of an aircraft. Originally, the main areas in this project were:

- Configuring the sensor data fusion algorithm
- Detection of failures and integrity monitoring in navigation systems

- Terrain database related applications

The licentiate thesis by Jan Palmquist from 1997 focused on the second item. It was also accompanied and followed by about 75 Master Theses as described in earlier annual reports, including [67, 66, 65, 64] presented this year.

The other two items have been transformed to a separate project: Sensor Fusion, see Project 11 below.

Project 10: Signal Interpretation and Control in Combustion Engines

Lars Eriksson is project coordinator and he also acts as responsible researcher together with Per Andersson.

Project Background

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 modeling and model-based methods that can handle dynamic effects.

Todays engines are controlled by empirically obtained and fixed engine maps. Further, if not using measurements internal in the cylinder like the ionization current, engines are basically controlled without direct feed-back 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.

Project Goal

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. Engines are already complex systems and the complexity is increasing as more degrees of freedom are made available for the controller. With the increased degrees of freedom, traditional design methods based on calibration of maps will be too time and resource consuming and model-based design methods will play an important role in the future. Therefore the goal is to investigate and develop models that are suitable for control and diagnosis design.

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.

Project Results 2004

Modeling, observer design, and control have been the focus during the year and the collaboration between industry and the research group has been intensified. The mean value engine model suitable for observer and control design that was delivered from this project to SAAB has been used extensively in the collaboration. A new engine was delivered to vehicular systems laboratory from SAAB and the methodologies developed for the model tuning and observer design were refined and successfully applied to the new engine [27, 25]. An important question in observer design is the selection of sensors and placements that give best possibilities to observe the system state and especially air-mass flow. This question was investigated using structural observability and published in [24].

The problem of estimating cylinder air-charge (CAC) on TC SI-engines have been studied and a new model that accurately describes CAC was presented at the SAE 2004 conference [28]. This model takes into account both fuel enrichment at high loads and varying exhaust back-pressure which is typical for TC engines it reduce model errors at rich conditions from 10% down to less than 3%.

A family of models that is important for the choice of controller set points, but where the standard models are too complex to be implemented in an engine control system, is in-cylinder pressure models. Work in this area was initiated in Lars Eriksson's PhD in 1999 and it continues [26, 29, 30]. Within this area there is also a fruitful collaboration with the diagnosis group (Project 2: Diagnosis and supervision of vehicle functions).

Project 11: Sensor Fusion

This project is carried out by Division of Automatic Control and Communication Systems in cooperation with SAAB Bofors Dynamics, SAAB Gripen and NIRA Dynamics.

Highlights

The highlights of the year are:

- The paper [50] was accepted for IEEE Transactions on Signal Processing. Journal of Adaptive Signal Processing.
- The sensor fusion work got international and national recognition by several major research grants which will support and extend the scope of ISIS sensor fusion:
  - EU FP5 project MATRIS for real-time tracking of cameras using inertial sensors and image information.
  - The Swedish research programme Intelligent Vehicle Safety System (IVSS) granted the application SEFS (SEnsor Fusion for Safety systems), where Chalmers and Volvo are partners.
  - The Swedish research council (VR) granted the project *Sensor informatics and sensor fusion.*

  These projects have in common that vision information is considered as a sensor in a sensor fusion framework.

Background

The research in the area of sensor fusion is focused on target tracking, navigation and positioning applications. The common denominator here is that these problems can be written as non-linear state space models with non-Gaussian noise:

$$\begin{aligned} x(t+1) &= f(x(t)) + w(t) \\ y(t) &= h(x(t)) + e(t) \end{aligned}$$

where the state vector contains position, velocity and other dynamical states, and the measurements come form sensors as gyroscopes, accelerometers, GPS, radar, *etc.* The filtering problem is to estimate the states given the measurements. The classical approach is to linearize the state space model, to assume Gaussian noise and then applying the Kalman filter. The particle filter provides a general algorithm for approximating *a posteriori* distribution of the states with arbitrary accuracy. The framework is particular suitable for *sensor fusion*, where sensor information of different kind is mixed with *e.g.* information from digital maps.

Projects

We have the last few years developed efficient and robust particle filter algorithms to approximate the a posteriori distribution of the state vector, and applied the algorithms to a number of applications:

- Complexity analysis of the marginalized particle filter [50].
- Application of the particle filter to robotics [22, 21] for accurate tool position estimation using accelerometers.
- Fundamental limitations of non-linear filtering (as the PF) for non-Gaussian linear systems [20, 49].
- Application of the particle filter for underwater navigation [55].

7 ISIS Publications 2004

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

Licentiate Theses

[1] Jonas Gillberg. Methods for frequency domain estimation of continuous-time models. Technical Report Licentiate Thesis no. 1133, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2004.

[2] Thomas Gustafsson. Maintaining data consistency in embedded databases for vehicular systems. Linköping Studies in Science and Technology Thesis No. 1138. Linköping University. ISBN 91-85297-02-X.

[3] Marcus Klein. A specific heat ratio model and compression ratio estimation. Technical report, 2004. LiU-TEK-LIC-2004:33, Thesis No. 1104.

[4] Erik Wernholt. On multivariable and nonlinear identification of industrial robots. Technical Report Licentiate Thesis no. 1131, Department of Electrical Engineering, Linköping University, SE-581 83 Linköping, Sweden, Dec 2004.

Journal Papers and Book Chapters

[5] M. Östring and Svante Gunnarsson. Recursive identification of physical parameters in a flexible robot arm. *Asian Journal of Control*, 6, Feb 2004.

[6] Mikael Norrlöf. Disturbance rejection using an ILC algorithm with iteration varying filters. *Asian Journal of Control*, 6(3):432–438, Feb 2004.

[7] Fredrik Gunnarsson. *Power Control in Wireless Networks - Characteristics and Fundamentals*, chapter 7, pages 179–208. Kluwer Academics, 2004.

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[9] Marcus Klein, Lars Eriksson, and Jan Aslund. Compression ratio estimation based on cylinder pressure data. *Provisionally accepted for Control Engineering Practice*, 2005.

Conference Papers

[10] David Törnqvist, Erik Geijer Lundin, Fredrik Gunnarsson, and Fredrik Gustafsson. Transmission timing - a control approach to distributed uplink scheduling in WCDMA. In *Proc. American Control Conference*, Boston, MA, USA, June 2004.

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[20] Gustaf Hendeby and Fredrik Gustafsson. On performance measures for approximative parameter estimation. In *Reglermöte 2004*, May 2004.

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