Control Systems Engineering Research Report 2000

1 Introduction

1.1 Overview

In this report we give an overview of the ongoing research projects at the Control Laboratory of the Faculty of Information Technology and Systems of Delft University of Technology.

The main goal of the Control Laboratory is to develop methods and tools to control complex nonlinear dynamic systems in order to improve their performance. The main research areas are:

- Intelligent modeling, control and decision making:
  black box and gray box modeling of dynamic systems with fuzzy logic and neural networks, and design of controllers using fuzzy set techniques.
- Distributed, hierarchical, and hybrid systems and control:
  analysis and control methods, multi-agent control systems, and implementation issues.
- Physical modeling and control:
  Lagrangian and Hamiltonian modeling and control frameworks (energy based) for different engineering domains
- Nonlinear analysis and control:
  nonlinear predictive control, sliding mode control, feedback linearization techniques, model and controller order reduction, development of tools for nonlinear control.

The main application fields are:

- Smart sensors: X-by-wire, traffic incident detection, sensors and actuator placement, laboratory on a chip, medical instruments.
- Robotics: mobile robots, interaction control.
- Power engineering: switching networks, power distribution and conversion.
- Traffic, transportation, mechatronics & robotics: autonomous and intelligent mobile systems, mobile robots, container transport, aircraft and satellite control, traffic control.
- Bioprocess technology: waste-water treatment, fed-batch bioprocesses.

The laboratory currently consists of 30 scientific and support staff: 8 permanent scientific staff, 10 PhD students, 1 postdoctoral researcher, 4 advisors, and 7 support personnel. The research activities are for a large part financed from external sources including the European Community (ESPRIT, Brite-Euram), the Dutch National Science Foundation (STW), the Delft University of Technology and by industry.
Additional information can be found at `http://lcewww.et.tudelft.nl/`.

1.2 People in 2000

Scientific staff

Prof. dr. ir. J. Hellendoorn
Ir. drs. R.A.M. van Amerongen
Dr. R. Babuška
Dr. ir. T.J.J. van den Boom
Dr. ir. B. De Schutter
Dr. ir. J.B. Klaassens
Dr. ir. J.M.A. Scherpen
Dr. ir. S. Stramigioli

PhD students & post-docs

J. Abonyi (until Mar. 31, 2000)
Ir. H.H.J. Bloemen
Ir. G.J.C. Copinga (until Feb. 29, 2000)
Ir. C.J.H. Engelen (until Jan. 31, 2000)
Drs. D. Ettes
K. Fujimoto
Ir. A. Hegyi
A. Ichtev, MSc
Ir. D. Jeltsema
R. Lopezlena, MSc
Ir. G. Monsees
Ir. M.L.J. Oosterom
S. Mollov, MSc
Ir. J.A. Roubos
Ir. M. Setnes (until Jan. 31, 2000)
Ir. P.J. van der Veen
Ir. B. Wams
Dr. L. Wessels

Non-scientific staff

C.J.M. Dukker
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D. Noteboom
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G.J.M. van der Windt

Advisors

Ir. P.M. Bruijn
Prof. ir. G. Honderd, em.
Prof. ir. H.R. van Nauta Lemke, em.
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1.3 Address and location

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2 Intelligent modeling, control & decision making

The focus is on the use of fuzzy logic, neural networks and evolutionary algorithms in the design, analysis and synthesis of models and controllers for nonlinear dynamic systems. Fuzzy logic systems offer a suitable framework for combining knowledge of human experts with partly known mathematical models and data. Artificial neural networks are effective black-box function approximators with learning and adaptation capabilities. Evolutionary algorithms are randomized optimization techniques useful in searching high-dimensional spaces.

2.1 Intelligent molecular diagnostic systems

Project members: L. Wessels, P.J. van der Veen, J. Hellendoorn

Sponsored by: DIOC-5: Intelligent Molecular Diagnostic Systems

It is the goal of the DIOC-5 (DIOC: Delft Interfaculty Research Center) program to produce an *Intelligent Molecular Diagnostic System* (IMDS). The IMDS will consist of two basic components: a measurement device and an information processing unit (IPU). The measurement device is a chemical sensor on a chip, which will be capable of rapidly performing vast numbers of measurements simultaneously, consuming a minimal amount of chemical reagents and sample (see Figure 1).

The IPU transforms the complex, raw measurements obtained from the sensor into output that can be employed as high-level decision support in various application domains. See [38] for a possible realization of the IPU.

Members of the Control Laboratory and the Information and Communication Theory Group are responsible for the realization of the Information Processing Unit. Unraveling the metabolic processes and the associated regulatory mechanisms of yeast is a very interesting application area for the DIOC-5 technology. We are focusing on problems associated with gene and protein levels, and will integrate this information with existing knowledge about metabolic processes developed at the Kluyver Laboratory (One of the DIOC-5 partners). More specifically, gene expression data and protein concentration measurements are employed

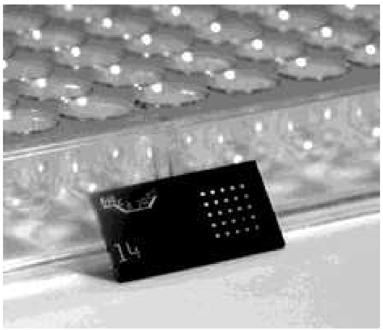


Figure 1: A prototype IMDS chip containing a matrix of 25 pico-liter wells.

to model the genetic networks, i.e. to postulate possible 'genetic wiring diagrams' based on the expression data. (See [37] for some preliminary results in this area.)

It is envisaged that at the end of this project, genetic network information, protein functional knowledge and metabolic models can be integrated into a single hierarchical model, capable of providing metabolic engineers with greater insight into the yeast metabolism.

For additional information see the IMDS Web page[1].

2.2 Model based optimization of fed-batch bioprocesses

Project members: J.A. Roubos, P. Krabben, R. Babuška, J.J. Heijnen, H.B. Verbruggen

Sponsored by: DIOC-6: Mastering the Molecules in Manufacturing, DSM Anti Infectives

Many biotechnological production systems are based on batch and fed-batch processes. Optimization of the product formation currently requires a very expensive and time consuming experimental program to determine the optima by trial and error. The aim of this project is to find a more efficient development path for fed-batch bioprocesses by an optimal combination of experiments and process models.

Fed-batch bioconversions have special characteristics due to their operating mode. During a common fed-batch run, several phases can be distinguished. These phases are characterized by difference in substrate consumption and metabolite production rates. The production process can be optimized through the implementation of an optimal feeding profile for the organism in time.

The two main research topics of this project are:

- *Development of a user friendly modeling environment for fed-batch processes.* The software tool must be able to use different types of knowledge coming from experts, experiments and first-principles, i.e., conservation laws. For this toolbox, new modeling methods such as fuzzy logic, neural networks and hybrid models will be used.
- *Iterative optimal experiment design.* First some basic experiments can be done to estimate some preliminary parameters for the system. The idea is to make a rough model to design the next experiment. First, a stoichiometric model is made and thereafter a

[1] http://www.ph.tn.tudelft.nl/~young/DIOC/IMDS.html

structured biochemical model that will be gradually improved according to the fermentation data. The main objective is to predict the right trends. The actual values are less important at the first stages.

Once the model is sufficient in terms of quantitative prediction of the production process for a variable external environment, it will be used to determine optimal feeding strategies for the reactor in order to improve product quality and/or quantity. These feeding strategies will be applied in an on-line process control environment.

2.3 Intelligent supervisory system for adaptive control of bioreactors

Project members: J. Abonyi, R. Babuška

Sponsored by: Senter

The control of biotechnical plants is a complex problem because a large number of processes and products exists. Bioprocesses are usually operated in batch or fed-batch mode. In fed-batch cultivation, the process dynamics evolve continuously during the operation, because the bioreactors receive variable additions of substrate along the culture which increase the liquid volume within the vessel and discrete events like anti-foam addition, and state transitions as changes from the growth phase to the production phase occur. Consequently, conventional linear controllers cannot provide good performance over the whole operating range of the fermentation process, due to its inherent nonlinear and time-variant properties. Moreover, the lack of adequate models hinders the application of advanced first-principle model-based control algorithms.

On possible solution is to use a self-tuning/adaptive control algorithm. These techniques are supposed to track changes in process dynamics and adjust the controller's parameters during the operation in accordance with a specified control objective. However, several problems limit the applications of parameter adaptive controllers to real industrial processes. For example, one of the disadvantages of conventional self-tuning controller is the continuous need for plant perturbation in order to supply sufficient excitation. That means, one often has to deliberately inject test signals to disturb possibly close-to-optimal plant behavior in order to avoid ill-conditioned parameter estimation. Moreover, the quality of the adaptive model based controller substantially depends on the adaptation results through the model accuracy. As the adapted parameters are immediately applied, any erroneous parameter estimates may result in unacceptably large changes in the control signal.

In order to avoid these problems, in this project an intelligent supervision system is designed to monitor the adaptation process and guarantee satisfactory control behavior.

2.4 Affordable digital fly-by-wire flight control systems for small commercial aircraft

Project members: M.L.J. Oosterom, R. Babuška, H.B. Verbruggen, G. Schram

Sponsored by: Brite/EuRam project ADFCS no. BRPR970524

This Brite/EuRam project is partly funded by the European Community. Its objective is to apply the Fly-By-Wire (FBW) technology in flight control systems (FCSs) to a smaller category of aircraft. In FBW digital flight control systems (DFCSs), there is no direct link between the control stick and pedals that are operated by the pilot and the control surfaces. All measured signals, including the pilot inputs, are processed by the flight control computer, which computes the desired control surface deflections. This setup enables the flight control engineer to alter the dynamic characteristics of the bare aircraft through the flight control laws (FCLs). Moreover, important features can be put into the FCLs, e.g., flight envelope protection, which will increase the safety level compared to aircraft with mechanical FCSs.

Our task in the project is to assess the benefits and to verify the validity of the fuzzy logic technology in the FBW DFCS design. This goal will be reached by developing applications concerning the FCL optimization and FCS redundancy management which handles fault detection, isolation and reconfiguration aspects of the system. For FCL optimization instead of adopting classic or modern control techniques, alternative design methods will be tested by using a fuzzy logic approach. For fault tolerance and reconfiguration capability fuzzy logic is adopted to rapidly detect failures, isolate them, and reconfigure the system to enable continued safe flight. In addition, the adaptation of this technology will allow better testability for maintenance purposes.

2.5 Fuzzy logic for spacecraft control: a feasibility study

Project members: C.J.H. Engelen, M.L.J. Oosterom, T.J.J. van den Boom, R. Babuška, H.B. Verbruggen

Sponsored by: European Space Agency (ESA)

This project concerns the design of a fuzzy logic controller for the re-entry mission of the X-38 Crew Rescue Vehicle. The X-38 is a spacecraft attached to the International Space Station (ISS) and it will serve as a re-entry vehicle for astronauts on-board. The X-38 will departure from its docking port of the ISS and after a short flight (about 40 minutes), a parachute will be unfolded above a particular landing site. The control problem is the stabilization and trajectory tracking of the attitude of the re-entry vehicle. The trajectory supplied is calculated to withstand the enormous heat-flux and to minimize G-forces, resulting in high angle-of-attacks and complex roll maneuvers used.

The project emphasizes on the search for an easy, efficient, cost-effective control design and development technique using fuzzy logic (FL). The ability to make a fast design and to produce smooth control actions around set points should make fuzzy logic a suitable candidate for use in spacecraft control applications. Successfully developed Guidance, Navigation and Control (GNC) software can be implemented in one of the many flight computer units on-board the X-38, which are used as back-up systems. The crew will have the capability to switch to any back-up system, control the orientation in orbit, pick a de-orbit site, and steer the parachute, if necessary.

The following figure shows a 1996 photograph of the vehicle taken at the NASA Dryden Research Facility. This X-38 scaled vehicle is about 8.6 m long, 4.4 m wide and weights about 7200 kg.

2.6 Fuzzy algorithms for the control of multiple-input, multiple-output processes

Project members: R. Babuška, S. Mollov, P.J. van der Veen, A. Gegov, J.A. Roubos

Sponsored by: FAMIMO Esprit project LTR 219 11

Partners

- IRIDIA, from the Université Libre de Bruxelles, Belgium
- Siemens Automotive, the industrial partner of the project, LAAS, Toulouse, France
- AICIA, University of Sevilla, Spain
- Department of Automatic Control, Lund Institute of Technology, Sweden
- Control Laboratory, Delft University of Technology, the Netherlands.

The Delft part of this project focuses on the use of fuzzy logic in model-based predictive control of multiple-input, multiple-output (MIMO) systems. Emphasis is put on:

- Data-driven identification of MIMO processes by means of fuzzy models. To this end, a number of techniques have been developed and a Matlab toolbox is available from the FAMIMO web site[2].
- Development of efficient optimization methods for the nonlinear fuzzy model. Techniques based on instantaneous extraction of local linear models from the fuzzy model and subsequent use of quadratic programming have proven to be effective. Also these tool have been packaged in a Matlab/Simulink toolbox.

[2] http://iridia.ulb.ac.be/~famimo/

- Additional issues related to the analysis and synthesis of fuzzy predictive controllers have been investigated. They include robust stability augmentation by means of signal-based methods (developed in cooperation with AICIA) and decoupling of MIMO loops.

The developed techniques have been tested on two simulation benchmarks:

- Waste-water treatment process [31]
- Gasoline direct injection (GDI) engine

Additional information can be found on the FAMIMO Web page.

2.7 Fuzzy control of multivariable processes

Project members: R. Babuška, S. Mollov, H.B. Verbruggen

Extensive research in fuzzy control has been devoted to single-input single-output processes, including modeling and control design aspects, analysis of stability and robustness, adaptive control. Fuzzy control provides effective solutions for nonlinear and partially unknown processes, mainly because of its ability to combine information form different sources, such as available mathematical models, experience of operators, process measurements, etc. Multivariable processes, however, have received considerably less attention, despite strong practical needs for multivariable control solutions, indicated among others from process industry, (waste)water treatment, or aerospace engineering. Yet, theoretical foundations and methodological aspects of multivariable control are not well developed.

This research project focuses on the use of fuzzy logic in model-based control of multiple-input, multiple-output (MIMO) systems. Main emphasis is put on:

- *Design aspect of the control system.* A number of techniques are available to develop (neuro-)fuzzy models of MIMO processes. There are, however, no generic solutions for designing an appropriate controller based on a (neuro-)fuzzy model. Among the important issues are: acquiring model suitable for applied the control method, tuning of the controller, use of uncertainty in the model, etc.

- *Framework for the analysis of the control system.* Before implementing a controller, important dynamic properties such as stability and robustness need to be analyzed. A methodological framework for this analysis must be developed for fuzzy systems, possibly by extending techniques known from linear and nonlinear system theory (e.g., linear matrix inequalities). An important aspect of multivariable control is the analysis of static and dynamic interactions among the variables.

- *State observation.* With most processes the states are not measurable or are heavily corrupted by disturbances. Observers can be used to reconstruct the unmeasured or corrupted variables. The use of fuzzy models of a suitable structure to design observers is an important research topic.

Besides theoretical and methodological developments, the project aims at testing and applying the developed techniques on practical problems [22, 21].

2.8 Fuzzy model based control with use of *a priori* knowledge

Project members: J. Abonyi, R. Babuška

A critical step in the application of model-based control algorithms is the development of a suitable model of the process dynamics. To effectively develop models, one needs to blend information of different nature: experience of operators and designers, measurements and first principle knowledge formulated by mathematical equations. The aim of this project is to design a fuzzy modeling framework that is suitable for the use of this information to generate control-relevant process models.

To incorporate *a priori* knowledge into data-driven identification of dynamic fuzzy models of the Takagi-Sugeno type a constrained identification algorithm has been developed, where the constrains of the candidate model parameters are based on knowledge about the process stability, minimal or maximal gain, and the settling time [3, 5]. The algorithm has been successfully applied in the on-line adaptation of fuzzy models.

When no *a priori* knowledge about the local dynamic behavior of the process is available, information about the steady-state characteristic could be extremely useful. Because of the difficult analysis of the steady-state behavior of dynamic fuzzy models of the Takagi-Sugeno type [1], block-oriented fuzzy models have been developed. In the Fuzzy Hammerstein (FH) model, a static fuzzy model is connected in series with a linear dynamic model [4]. The obtained FH model is incorporated in a model-based predictive control scheme. Results show that the proposed FH modeling approach is useful for modular parsimonious fuzzy modeling and fuzzy model-based control of nonlinear systems [2].

2.9 Fuzzy modeling in finance

Project members: D. Ettes, R. Babuška, H.R. van Nauta Lemke

Businesses in the financial world, like banks, insurance companies and pension funds have to cope with a lot of uncertainty while making important decisions. To help in this decision process, scientists have tried to model the financial world for over a century, but due to the high complexity, no model can be found that is applicable in all situations. Therefore, financial businesses usually use experts to make most of the decisions.

The most important issue in the financial world is risk. Whenever a company makes investments, it is important to know how big the risks are that the company takes. A company's investment strategy needs to be based on the risk the company is willing to take. To be able to quantify the risk an investor takes his decisions have to be formalized. The investment risk of a company cannot be quantified when the investment decisions are based on a hunch of an expert.

In this project, our goal is to build a system for investment decision-making that can be tailored to the risk profile of the investor. To model the decision process, we use fuzzy models. Fuzzy models are used because of their interpretability, flexibility and nonlinearity.

Our first step is to make a general framework for modeling the advice of experts in Technical Analysis. Different time series are used to model the advice of the experts. The advice can be buy, hold or sell. The second step is to build a stock picking system that manages a portfolio based the advice models of different stocks. Now the influence, of the risk profile of the investor on the advice models and the stock picking system needs be investigated. This is necessary to be able to fine-tune the system for every risk profile an investor can have.

Later, advises of experts in fundamental and quantitative analysis can be used to improve the investment system.

2.10 Neuro-fuzzy modeling in model-based fault detection, fault isolation and controller reconfiguration

Project members: M.H.G. Verhaegen, J. Hellendoorn, R. Babuška, S. Kanev, A. Ichtev

Sponsored by: STW

The demand for increased efficiency in various branches of industry, such as manufacturing, aerospace, process and energy production industry leads to an increased degree of automation of the production process. In order to meet this demand while at the same time maintaining or improving the quality and safety, it is necessary that the (complex) control system is *fault tolerant*. This means that the effects of failures, such as component failures, actuator and sensor failures, on the quality and safety of the production process are minimized. The latter criterion is of course context dependent and may e.g. result in a safe shut-down of the process unit avoiding casualties or modifying the performance specifications to safely continue operation under minimal economical losses.

An important class of approaches to design fault tolerant control systems, consists of a so-called model-based Fault Detection and Isolation (FDI) part which should detect whether a failure has occurred and to localize it, and Controller Reconfiguration (CR) part which should modify the control structure or parameters to maximize production quality and safety. The two key elements in designing these two parts are the development of a mathematical model and a suitable decision mechanism to localize the failure and to select a new controller configuration. Despite the fact that neural networks have been widely investigated for this purpose, they have demonstrated a number of shortcomings, such as the lack of analytical tools to analyze their performance (stability, robustness, etc.), that hamper their practical acceptance in fault diagnosis advisory systems.

In this project we represent the mathematical model and derived observers as a composition of local models, each describing the system in a particular operating regime or failure mode. The switching between models will be determined by fuzzy set membership function, which may be modeled as neural networks and tuned by means of neuro-fuzzy learning algorithms. This approach exhibits a number of advantages that will be fully explored in this research project. One advantage is that the set of rules by which the model is represented can be interpreted by the operators. This allows to extend and update these models with their expert knowledge improving both the reliability of the models and their acceptance and validation. The mode-switching model will be embedded in the framework of hybrid system theory and heterogeneous control theory, paving the way to put FDI and CR in a fundamental framework to analyze the robustness, stability and performance by means of analytical tools rather then by exhaustive simulation runs only. The advantages pressured in this research will enhance the acceptability of FDI and CR in industrial applications.

2.11 Estimation of respiratory parameters via fuzzy clustering

Project members: R. Babuška, M.S. Lourens, A.F.M. Verbraak and J. Bogaard (University Hospital Rotterdam)

The results of monitoring respiratory parameters estimated from flow-pressure-volume measurements can be used to assess patients' pulmonary condition, to detect poor patient-ventilator interaction and consequently to optimize the ventilator settings. A new method is being investigated to obtain detailed information about respiratory parameters without interfering with the expiration. By means of fuzzy clustering, the available data set is partitioned into fuzzy subsets that can be well approximated by linear regression models locally. Parameters of these models are then estimated by least-squares techniques. By analyzing the dependence of these local parameters on the location of the model in the flow-volume-pressure space, information on patients' pulmonary condition can be gained. The effectiveness of the proposed approaches is studied by analyzing the dependence of the expiratory time constant on the volume in patients with chronic obstructive pulmonary disease (COPD) and patients without COPD.

3 Distributed, hierarchical, and hybrid systems & control

Hybrid systems typically arise when a continuous-time system is coupled with a logic controller, or when we have a system in which external inputs or internal events may cause a sudden change in the dynamics of the system. So hybrid systems exhibit both continuous-variable and discrete-event behavior. Due to the intrinsic complexity of hybrid systems control design techniques for hybrid systems we could either focus on special subclasses of hybrid systems, or use a distributed or hierarchical approach to decompose the controller design problem into smaller subproblems that are easier to solve. In our research we use both approaches.

3.1 Optimal switching sequences for first order linear hybrid systems with saturation

Project members: B. De Schutter

Hybrid systems arise from the interaction between continuous variable systems (i.e. systems that can be described by a system of difference or differential equations) and discrete event systems (i.e. asynchronous systems where the state transitions are initiated by events; in general the time instants at which these events occur are not equidistant). In general we could say that a hybrid system can be in one of several modes whereby in each mode the behavior of the system can be described by a system of difference or differential equations, and that the system switches from one mode to another due to the occurrence of an event (see Figure 2).

In this project we consider a special class of hybrid systems: first order linear hybrid systems with saturation. A system that belongs to this class can operate in several modes or phases; in each phase each state variable of the system exhibits a linear growth until a specified upper or lower saturation level is reached, and after that the state variable stays at that saturation level until the end of the phase. A typical example of such a system is a traffic signal controlled intersection (see also Project 3.2). We have developed model predictive

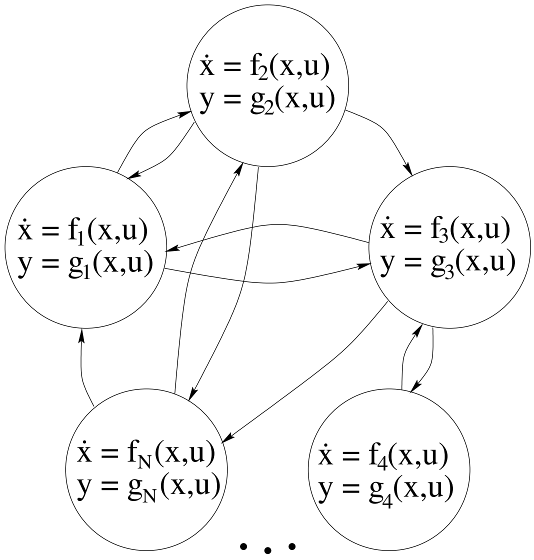


Figure 2: Schematic representation of a hybrid system.

control methods to determine optimal switching time sequences for first order linear hybrid systems with saturation that minimize criteria such as average queue length, worst case queue length, average waiting time, and so on [13, 15]. First we have shown how the Extended Linear Complementarity Problem, which is a mathematical programming problem, can be used to design optimal switching time sequences. Although this method yields globally optimal switching time sequences, it is not feasible in practice due to its computational complexity. Therefore, we have also developed methods to compute suboptimal switching time sequences. If there is no upper saturation then for some objective functions the globally optimal switching time sequence can be computed very efficiently. Furthermore, by introducing some additional approximations the problem reduces to a linear programming problem.

3.2 Optimal traffic control

Project members: B. De Schutter, T. Bellemans (K.U.Leuven, Belgium)

Sponsored by: FWO project ICCoS (Identification and Control of Complex Systems)

Congestion and traffic jams are one of the major socio-economic problems of today. Since building new roads is not always a feasible option, one of the most effective measures in the battle against traffic congestion seems to be a better control of traffic. Possible approaches to control traffic flows are traffic signals, variable message signs, dynamic route information panels, ramp metering, "green waves", route directives, radio broadcast messages, etc.

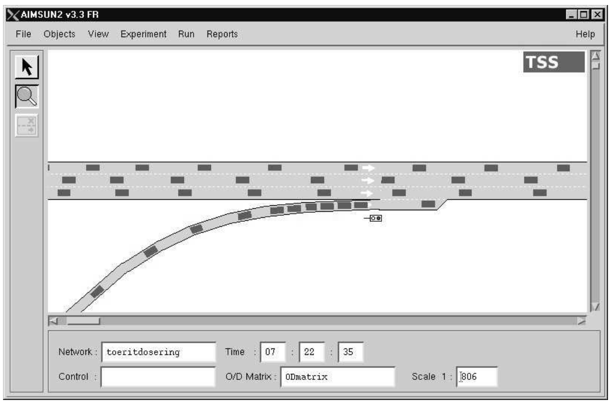
In this project we concentrate on two kind of traffic control measures:

- optimal traffic signal control
  First we considered this problem for a single intersection: given the average arrival and departure rates of vehicles at the intersection, we have developed methods to efficiently compute (sub)optimal traffic signal switching schemes that minimize a criterion such as average queue length, worst case queue length, average waiting time, . . . , thereby

augmenting the flow of traffic and diminishing the effects of traffic congestion [14, 16]. The approach we have used to solve the problem is based on hybrid systems (see also Project 3.1). Our current research is aimed at extending these results to networks of intersections.

- optimal ramp metering (in cooperation with K.U.Leuven, Belgium)
  In ramp metering a traffic signal is put at the on-ramp of the highway. When the signal is green, one car at the time is allowed to enter the highway. The switching scheme of the traffic signal (i.e. the occurrence of green periods) should be controlled in a such a way that the additional flow coming from the on-ramp does not cause the traffic flow on the highway after the on-ramp to exceed the critical density. In this way a smooth flow of traffic is guaranteed and traffic jams are prevented. Note however that the waiting time for the vehicles on the on-ramp should also be minimized. The resulting problem can be solved using nonlinear optimization. However, because of its computational complexity this approach is not feasible for on-line adaption of the ramp metering policy to changes in traffic patterns. Therefore, we are now using several techniques (including fixed structure state feedback controllers, neural controllers, fuzzy controllers, ...) that will lead to (suboptimal) ramp metering strategies that can be used for on-line computation and adaptation.

For both the traffic signal control problem and the optimal ramp metering problem, it is usually not feasible to test the computed (sub)optimal strategies directly in the field. Therefore, we use micro simulation to compare the performance and efficiency of the different solutions. In micro simulation the movements of each individual vehicle are simulated (see figure). In that way the advantages and disadvantages of each traffic signal switching strategy or ramp metering strategy can be determined.



Screen shot of a micro simulation of ramp metering.

3.3 Advanced control techniques for optimal adaptive traffic control

Project members: A. Hegyi, B. De Schutter, J. Hellendoorn

Sponsored by: AVV (Transport Research Centre, Ministry of Transport, Public Works and Water Management, The Netherlands)

The overall framework of this project is dynamic traffic management (DTM). We mainly address systems and control issues of DTM. More specifically, we investigate the possibilities and advantages of using advanced control techniques in optimal adaptive traffic control.

Traffic patterns change during the day and depend on external influences such as weather conditions, incidents, holidays, and so on. In order to obtain optimality traffic control policies should adapt to these changes. Adaptive controllers take the changes in the traffic system and the external conditions into account and in that way they can deal with the changes in the traffic patterns. Therefore, we consider adaptive traffic controllers in this project.

When a certain traffic control measure is taken, drivers will adapt their behavior so as to minimize the possible negative impacts of the control measure on their travel times. Most traffic models do not take these reactions of the drivers into account. So if no special measures are taken, we could end up in a kind of cycle in which the control center adapts its control strategy to the new behavior of the drivers, whereupon the drivers again adapt their behavior, and so on. In the worst case this could lead to instabilities and other undesired effects. Therefore, it is important that while designing traffic control strategies possible reactions of the drivers are already taken into account. This leads to the design of anticipative traffic controllers.

We also investigate anticipatory traffic control in this project, but with a limited time horizon (say on the level of hours). Indeed, short-term adaptations (such as changes in the route choices) can be measured and can sometimes be modeled reasonably well. However, long-term effects (such as changes in mode of transportation and even changes in location of work or settlement) are far more difficult to measure and model. Therefore, we only take the short-term effects into account in the design of optimal traffic controllers.

Figure: Ramp metering on the A13 highway in Delft-Zuid.

3.4 Fuzzy decision support system for traffic control centers

Project members: A. Hegyi, B. De Schutter, S. Hoogendoorn (Civil Eng., TU Delft), R. Babuška, H. van Zuylen (Civil Eng., TU Delft)

Sponsored by: AVV (Transport Research Centre, Ministry of Transport, Public Works and

Water Management, The Netherlands)

Modern state-of-the-art traffic control centers use dynamic traffic management measures such as ramp metering, dynamic route information panels (with indications of congestion, traffic jams and alternative routes), or variable message signs with maximum speeds per lane (in order to obtain speed harmonization and thus smoother traffic flows) to control the traffic flows on highways and urban ring roads. Regular, recurring congestion can usually be solved or alleviated by using local measures. However, operators in traffic control centers often face a difficult task when non-recurring, non-predictable congestion occurs (e.g. as a consequence of severe incidents). In such situations, the local measures are usually insufficient and often an intervention on the network level is required to resolve the congestion and to return to a "normal" traffic situation. Thus, the effects of the congestion are attenuated by redirecting the traffic flows in a larger part of the network. The operator then has to assess the severity of the congestion, predict the most probable evolution of the state of the network, and select the most appropriate measures. This is a complex task, which requires specialist knowledge and a lot of experience, which often can be obtained only after extensive training. As a result, the approaches used by human operators in traffic control centers are in general not structured and not uniform.

The aim of this project is to provide a decision support tool to assist the operators of traffic control centers in their decisions when they have to take the appropriate measures to deal with non-recurring, non-predictable congestion. This system should help the operators to react in a uniform and structured way to unusual situations. Since we want to create a decision support system that allows for an easy and smooth interaction with the human operators, with a decision process that is both intuitive and can be explained in linguistic terms, we have opted for a decision support system based on a fuzzy knowledge base. The inputs for the fuzzy decision support system are the current state of the network. First the inputs are fuzzified, i.e. translated into linguistic terms (e.g. a measured traffic density could be classified as "uncongested", "regular", "dense" or "congested" traffic, with a specific membership degree for each class). Next the inputs are fed to a fuzzy rule base. The rules for this knowledge-base are obtained from the manual for traffic control centers and from other sources such as experienced operators, traffic experts, and simulation and policy evaluation experiments. The output of the system is a linguistic characterization of the possible actions to be taken and their predicted effectiveness in the current situation.

4 Physical modeling and control

The physical systems of interest here are typically systems that can be obtained by first principle modeling. In general the systems descriptions will be such that the physics of the system is obviously present, and can be used for analysis and control purposes. The methods include, but are not restricted to, dynamical modeling with help of Lagrangian and Hamiltonian formalisms.

4.1 Control of a jumbo container crane (JCC project)

Project members: J.B. Klaassens, G. Honderd, H.R. van Nauta Lemke

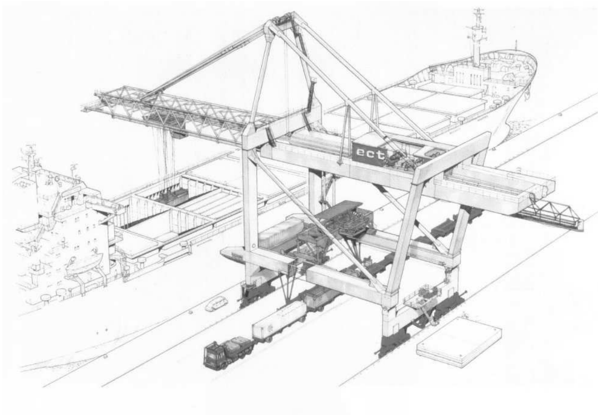
Sponsored by: Connekt

The Jumbo Container Crane (JCC) project is a part of the FAMAS (First, All Modes, All Sizes) program, initiated by the Centre of Transport Technology (CTT) in 1996. The goal of the program is to develop a new generation of container terminals capable to handle all modalities of all sizes with an equal service level. This concerns all modalities, including the within ten years coming Jumbo Container Vessel. Vessels with a capacity of eight to ten thousand TEU (Twenty Feet Equivalent). To accomplish the program's goal, a highly automated terminal will be developed. Handling containers with a throughput of 500.000 TEU a year or more can only be done economically and efficiently by robotizing stacking and terminal transport. The goal of the JCC project is to develop container cranes which can handle a Jumbo Container Vessel within 24 hours. The JCC project has the following participants: NELCON B.V., ECT, Siemens Nederland N.V., DUT Faculty of Mechanical Engineering and Marine Technology: Transport Technology and DUT Faculty of Information and System Technology, Control Laboratory.

The Control Laboratory contributes with the following research activities:

- Development of 2D and 3D mathematical models of the container crane.
- Design and construction of a laboratory scale model of the container crane.
- (Time)optimal trajectory generation. This research provides a trajectory for the container crane load which minimizes the transfer time for the container. A trajectory should obey the following restrictions:
    1. a set of equations (the systems dynamics),
    2. a set of inequalities (the constraints like the maximum speed and acceleration, but also the constraints caused by other objects to be avoided),
    3. an initial state (the end point of the container). The transfer time is expressed in a cost-function. Our task is to provide a trajectory which transfers the state from the initial state to the final state with minimum cost without offending any of the above restrictions. Various techniques like dynamic programming or Pontryagin's maximum principle, are tested.
    4. a final state (the end point of the container). The transfer time is expressed in a cost-function. Our task is to provide a trajectory which transfers the state from the initial state to the final state with minimum cost without offending any of the above restrictions. Various techniques like dynamic programming or Pontryagin's maximum principle, are tested.
- Design of robust controllers with the potential of fully automatizing the process. The torque patterns of the cat motor and the hoist motor are controlled in such a way that the container can track the time-optimal trajectory.
- Stabilizing swing and skew of the container.
- Sensors for the position, the swing angle and all other relevant variables of the payload.
- Control of the hoist and cat motor.

- The possibilities of a fuzzy supervisory controller for adjusting "low-level" controllers to the specific modes of operation, are studied.



Sketch of the jumbo container crane.

4.2 Field-oriented and intelligent control of AC rotating and linear electrical drives

Project members: J.B. Klaassens, E.A. Lomonova

The AC rotating and linear motors are attractive candidates for many applications of electrical driven with computer-integrated control in the field of machine tools, industrial robots, etc. Flux vector control is implemented in the microprocessor or digital signal processor and results in enhancing performance of the AC electrical drives. Toolboxes are developed for AC electrical drives (with induction, synchronous, brushless, reluctance or switched reluctance motor) in the form of the integrated operation of electrical machines, static converters, electronic control circuits and different mechanical loads. The computer aided design tools verify dynamic behavior, control algorithms, performance characteristics (one, two and four quadrants of operation), energy transferring mechanism, etc. The flexible connection of the standardized blocks (coordinate transformations, pulse modulators, switching networks) allows the modification of the electrical drive architecture and structure, introduction of direct and indirect control methods, implementation of the sensorless control.

4.3 X-by-wire

Project members: J.B. Klaassens, S. Stramigioli, E. Holweg (SKF)

Sponsored by: SKF

The objective of this project is to achieve a framework for the introduction of safety related fault tolerant electronic systems without mechanical backup in vehicles (so-called "x-by-wire systems"). The "x" in "x-by-wire" represents the basis of any safety-related application, such as steering, braking, power train or suspension control systems. These applications will greatly increase overall vehicle safety by liberating the driver from routine tasks and assisting the driver to find solutions in critical situations. Highly sophisticated future vehicle applications such as driver assistance or autonomous driving need computerized control of the driving dynamics. This requires that driver requests be sensed and interpreted appropriately so as to take proper account of the current driving conditions and environmental influences. These requests have to be translated into optimum steer, brake, and acceleration maneuvers. In the aerospace industries the topic of dependable electronics system has been the subject of intensive investigations over many years. Other solutions are available in transportation in general, e.g. military vehicles, ships, trains, as well as in safety critical industrial applications like nuclear power plants. Research is done in cooperation with SKF.

4.4 Physical systems and control

Project members: S. Stramigioli

This project is concerned with the development of controllers which are equivalent to physical systems. As shown in [26] this kind of controllers are necessary when the robot to be controlled interacts with the environment. The theory used can be found in Generalized Port Controlled Hamiltonian theory [20] where any physical system in explicit form can be represented by the following non linear differential equations:

$$\begin{aligned} \dot{x} &= (J(x) - R(x))\frac{\partial H(x)}{\partial x} + G(x)u \\ y &= G^T(x)\frac{\partial H(x)}{\partial x} \end{aligned}$$

in which x is the state, $H(x)$ the Hamiltonian function, $J(x)$ is skew-symmetric and $R(x)$ positive semidefinite. Both the plant, the controller and their interconnection can be then written in the previous form.

In the modeling of 3D mechanical systems some new results have been found which relate screw-theory to Lie-group theory [27].

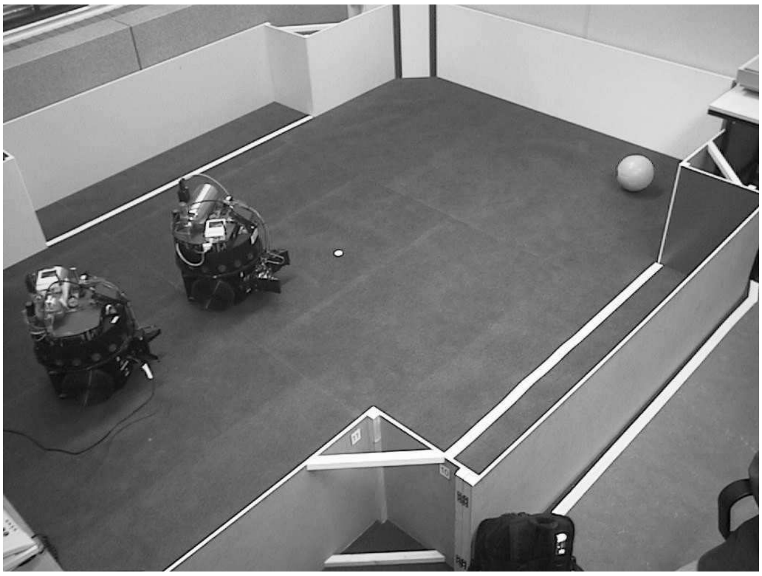
4.5 Autonomous robotics and Robocup

Project members: S. Stramigioli, P. Jonker, W.J.M. van Geest and R.M.A. van Puffelen

This project is concerned with the control of mobile robots playing soccer. The scientific concepts investigated in the project include the control of systems with non-holonomic constraints [32], collision avoidance and multi-agents control [26].

The concepts here developed can be framed in autonomous systems which can be used in real life for tasks which can be either dangerous or time-consuming for humans like the inspection of nuclear plants or the removal of mines.

Other direct applications can be found in transportation and traffic.

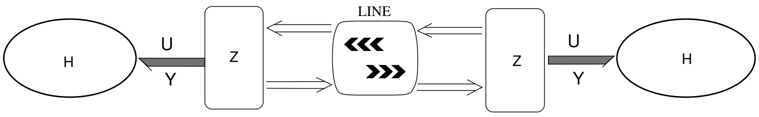


Experimental set-up.

4.6 Geometric Telemanipulation

Project members: S. Stramigioli, A. van der Schaft, B. Maschke

This project is concerned with the study of tele-manipulation of Hamiltonian Systems with time delays in a coordinate free way.



In the figure H indicates a Hamiltonian system and the Z blocks the scattering transformation.

Using a geometric scattering representation, passivity with time delays can be achieved.

Future research will address the performance of such systems. Experimental results have also confirmed the results [28].

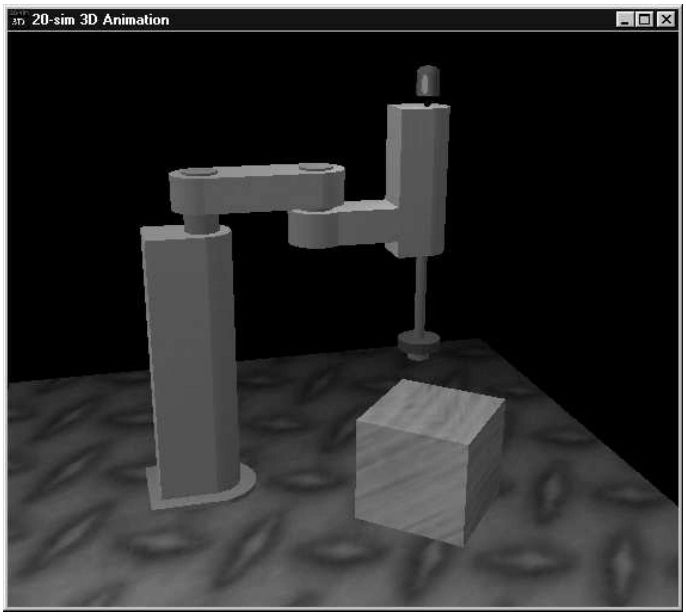
4.7 Multibody modeling using screw bondgraphs

Project members: S. Stramigioli

Using bond graphs, screw theory and Lie groups, an extremely efficient way of modeling and simulating multi-body systems has been found.

The development of models in this context and the simulation kernel is done in cooperation with Control Lab Products which is going to implement the results in the modeling and simulation package 20sim[3] which even allows real time 3D visualization.

[3]http://www.20sim.com



One of the main advantages is the topological simplicity and speed improvements in modeling and simulation of multi-body systems.

4.8 Towards a web-based study support environment to improve study effectiveness in teaching automatic control courses

Project members: G.J.C. Copinga, J.M.A. Scherpen, B. De Schutter

The ideal master-pupil relationship that has characterized education during ancient (Greek, etc.) times was individually based and took place on an almost 24h/day basis for extended periods of time. The expertise or knowledge of the teacher (master) was transferred continuously to the student (pupil) and furthermore the teaching material and pace was adapted to the student's individual progress, interests, etc. The goal of teaching is very well phrased by the following Chinese saying "*Tell me and I'll forget, Show me and I may remember, Involve me and I'll understand*".

Interactive tools, which are accessible to the students at any time through Internet, are considered as a great stimulus for developing the student's engineering intuition. These interactive tools attempt to 'demystify' abstract mathematical concepts through visualization in concrete (realistically) chosen examples.

Though the interactive tools to visualize and concretize control engineering concepts can be a great asset for training good control engineers, to improve study effectiveness it is important that the students use them at the right time. Further, Automatic Control Engineering courses typically contain a number of 'bottleneck' topics, generally related to the analysis of the practical applicability of control engineering techniques. This means that for improving study effectiveness, not only the development of nice interactive visualization tools is necessary but also two additional measures need to be taken:

1. The creation of a web-based study support system to inform students and to communicate with them at all times. Communication here means exchanging (electronic)

messages as well as delivering study material, such as the used transparencies, Matlab code, etc.

2. Offering frequent advice on student progress in mastering the course content. This advice is based upon the student's performance in electronically accessible self-test exercises. These exercises are dedicated both to the bottleneck topics in the course as well as to the refreshment of elementary material that has been treated in previous courses.

In this research project a web-based study support environment was designed and developed based on these two measures for improving study effectiveness. The environment was initially used in an introductory course on System Identification within the curriculum of electrical engineering. At the moment the development of this environment continues for other courses within the curriculum of electrical engineering.

The evaluation so far shows that students are very positive about the design of the environment and that, in their opinion, the environment improves their study effectiveness. Other observations that support this conclusion are the fact that the students are more stimulated to attend the lectures (students take more responsibility for their own learning), students are provided with more opportunities to practice the learning material, the increase in the communication/interactivity between students and teacher, and students among each other, etc.

4.9 Subspace model identification

Project members: B.R.J. Haverkamp, M.H.G. Verhaegen

At the Systems and Control Engineering Group a family of powerful identification algorithms has been developed over the resent years. These algorithms are commonly known as Subspace Model Identification (SMI) algorithms. These algorithms were originally developed for discrete time LTI systems. Firstly our research aims to the extend these algorithms to new model types, such as continuous time models, linear time-varying models. Also types of non linear models, such as bilinear systems, are investigated. Secondly we apply the developed algorithms to practical problems in industry.

The SMI algorithms, developed in this laboratory over the resent years are grouped in a Matlab toolbox. This toolbox, called the SMI toolbox was first released in 1997, and consists of a number of routines to solve three general types of identification problems. Development of the second edition of this toolbox is underway, and we hope to deliver the result at the end of 1999. The toolbox is freely available for academic purposes from
`http://lcewww.et.tudelft.nl/~haver/smi/smi.html`.

Because many of the SMI algorithms are computationally intensive, ways are sought to improve the speed of the routines. Recursive algorithms are developed to reduce the computational complexity for online estimation. Another source of improvements can be found in writing the routines in higher programming languages such as FORTRAN and C++, using specialized libraries like LAPACK for the efficient linear algebra routines. Also the use of specialized hardware such as digital signal processors (DSP) has been researched.

4.10 Bounding uncertainty in subspace identification

Project members: T.J.J. van den Boom, B.R.J. Haverkamp

In this project we aim at the estimation of the uncertainty on models, identified using subspace identification methods.

The fully parameterized state-space is estimated using the popular subspace model identification method moesp. In the recent years, subspace model identification (SMI) has become a popular tool for the identification of state-space models. It provides a robust and accurate method for the identification of dynamical systems under the influence of disturbances. They are being used in many different practical applications.

The uncertainty region is specified in a polytopic description. This description is a powerful and elegant way to describe the parametric uncertainty set in the case of state-space models. For plants in an polytopic uncertainty description, robust controller can be designed using optimization techniques based on Linear Matrix Inequalities (LMI). For this type of optimization problems fast and reliable algorithms exist that solves the problem in polynomial time.

The key in this method is the calculation of the first or higher order approximation of the relation between the perturbation on the data and the error on the elements in the identified state-space matrices. Using this approximation one can find a polytopic description of the uncertainty region of the identified model. In a final step, the dimension of the polytopic description can be reduced.

Also the N4SID and CVA subspace identification algorithms can be handled by the above method, since the three algorithms closely related.

4.11 Modeling and control of switching electrical networks

Project members: J.M.A. Scherpen, J.B. Klaassens, D. Jeltsema

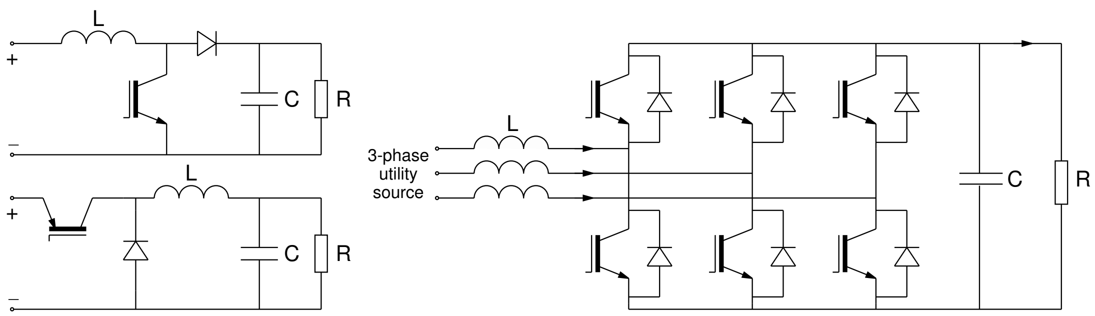
Switching networks are based on the combination of controllable switches and components in the form of inductors, capacitors, transformers and resistors. This class of networks describes in form and function the most families of power electronic circuits. The nominal operation in many switching networks involves a periodic steady state, focused on situations in which circuit operation and behavior are the same from cycle to cycle. We also have to deal with the consequences of the disturbances or errors that cause circuit operation to deviate from the nominal operation. We approach these type of systems from a physical modeling point of view, i.e., we use Hamiltonian and Lagrangian modeling techniques, develop schemes to do this algorithmically, and use these models for designing controllers based on the physics. One of the major advantages of this method is that we can incorporate nonlinear phenomena, and features of the network, which in the end will cause the closed loop systems to operate well, even if there are large set-point changes, or deviations from the nominal operation point. We refer to [24] for first results in this ongoing research project, which presently focuses on incorporating non-ideal phenomena in the models. This research is partly a collaboration with R. Ortega, SUPÉLEC, Gif sur Yvette, France, and with W.L. de Koning, and J.W. van der Woude, TU Delft.

4.12 Analysis and design of nonlinear control systems for switching networks

Project members: D. Jeltsema, J.M.A. Scherpen, J.B. Klaassens

Switching electrical networks are nowadays essential for high-performance energy control for a large variety of applications. This varies from simple DC-DC, AC-DC, DC-AC and AC-AC converter structures for use in commercial electrical apparatus, to high tech structures for use in for example space and non-civilian applications. The basic ideal configuration of a power converter is generally based on the combination of controllable (semiconductor) switches and (filter) components in the form of passive components like inductors, capacitors and transformers.

In the last thirty years this area has undergone a wealth of practical and theoretical developments, mainly done in the field of power electronics. These developments and studies where mainly concerned with small signal (linearizing) analysis based on averaging techniques like pulse-width modulation (PWM), and related, linear PID control techniques, static behavior, ripple analysis, etc. The aim of this project is to consider the general structure of switching electrical networks. We approach these systems from a physical modeling point of view, i.e. we use physical system theoretic descriptions (large signal) based on a Lagrangian and/or Hamiltonian framework, and we develop schemes to do this algorithmically. We will take into consideration the involvement of several classes of non-ideal physical effects. Further research also includes an extensive development to include all possible topologies and structures into the frameworks including systems with multiple switches.



The general modeling framework will be used for analysis purposes, and for giving specific choices for the best physical variables for controller design. These choices are important to obtain a better overall performance (in terms of overshoot, disturbance rejection, etc.) of the closed loop system. The topology of the switching network is decisive for the (in-)stability of the zero-dynamics, i.e. for being a (non-)minimum phase system. Study of the zero-dynamics is mainly of importance for the controller design. Furthermore, we study possible improvements by developing (nonlinear) control schemes that are based on the physics and that are generally applicable to this type of systems. If possible, by the new set-up from a system and control point of view, new switching network topologies will be developed, resulting in converter structures that are fulfilling specific demands of high tech applications like in e.g. space and non-civilian applications.

5 Nonlinear analysis and control

The nonlinear analysis and control theme covers mainly nonlinear techniques that have several relations with the other three main themes of the Control Laboratory. Nonlinear control methods like sliding mode control, dynamic model inversion and nonlinear predictive control are included in the projects. Furthermore, analysis and model reduction techniques, based on system realization methods are presented in the projects at hand. Applications of the methods of the theme are typically found in the process industry, car industry and several others.

5.1 Robust control of nonlinear systems using neural networks

Project members: B. Wams, T.J.J. van den Boom, H.B. Verbruggen

Sponsored by: STW

One of today's trends in modern control is finding faster an more reliable solutions for highly nonlinear control problems in constrained environments. This urge is originates from the need for controllers for industrial processes that are characterized by frequent changes in the operating conditions caused by varying quality of raw material, changing product mix, changing product requirements, etcetera. Moreover, many industrial processes exhibit a highly nonlinear behavior across the operating range, they are often subjected to physical constraints in their process operation and they often have to follow safety limitations as well as strict environmental regulations. All these aspects increase the overall complexity of the control problem and for solving these complex control problems conventional linear control methods can no longer be applied. When the complexity of the control problem increases, usually there is not enough knowledge about the system available in order to design a controller with satisfactory performance. In these cases, the use of a device that can abstract information about the system from input-output data only seems inevitable. Artificial neural networks can be used as such a device since they can approximate any continuous nonlinear function to any desired accuracy. Further, they have the ability to generalize with respect to new data, which means that they keep learning during operation. These features makes them very promising for application to modeling and control of nonlinear systems. We will focus on the incorporation of neural networks in Model Based Control. The design of a model-based control system relies heavily upon an explicit mathematical model of the system under control. In many cases such a model is very difficult to find, due to for instance lack of knowledge about the system or the presence of strong nonlinear dynamics in the behavior of the system. For this reason conventional control systems are usually based on a linearized and highly simplified mathematical model of the system under control. The use of simplified models in model based control usually leads to a decrease of performance of the overall system. In situations where conventional modeling techniques fail to provide a sufficiently good model, neural networks can be an outcome because of their powerful capabilities of modeling nonlinear systems. Moreover, we will focus on the quantification of the modeling errors that occur when neural networks are used for modeling [33, 36], since stability and performance properties of any model-based control scheme is related to the modeling error. Of particular importance is that when bounds can be given on the modeling error, neural networks can be used in the model-based predictive control scheme as described earlier [34, 35]. For this controller, system stability and a level of performance can be guaranteed, so it then can be applied to real-world applications for which conventional controllers fail to establish a satisfactory performance.

This project is done in corporation with the University of Amsterdam, Computer Science Group, and is part of STW-project AIF 44.3595.

5.2 Robust control using neural networks

Project members: T.J.J. van den Boom, M. Ayala Botto, B. Wams

The aim of the project is to investigate the possibilities of the application of neural networks to the robust control of dynamical systems. Currently the design of control systems relies heavily upon an explicit mathematical model of the system. However, such an model is often very difficult and sometimes impossible to find. For this reason conventional control systems are usually based on a linearized and highly simplified mathematical model of the dynamics of the system. Experiences of several research groups involved show that neural networks, which are able to learn a non-linear model from examples, can successfully be applied for the control of non-linear systems [6, 7, 29]. A second advantage is that neural networks are adaptive, in the sense that they keep learning during operation. This allows for continuous improvement of the controller while in operation.

However, little is known about the stability and robustness of control systems containing neural networks. Convergence has been proven for simple systems, but for complex systems neural networks have to generalize well in high dimensional spaces. In this project the link between accuracy of function approximation with a neural network and the stability of the system is a main goal to be established. The aim is to develop a robust model-based control scheme using a nonlinear (neural network) model. Of particular importance is that when bounds can be given on the modeling error, robust control schemes for such systems must be developed which lead to a guaranteed stable control system [33, 34]. The project will specifically investigate the relationship between bounds on the network error and stability of the system. If this is achieved, neural control can be applied to real-world applications with guaranteed robustness properties.

This project is done in corporation with the University of Lisbon, IST and is closely related to Project 5.1.

5.3 The robust standard predictive control problem

Project members: T.J.J. van den Boom, R.A.J. de Vries, H.B. Verbruggen

In this project the standard predictive control problem (SPCP) is studied. The SPCP consists of one extended process description with a feedback uncertainty block. The most important finite horizon predictive control problems can be seen as special realizations of this SPCP. The SPCP and its solution are given in state-space or polynomial form. The objective of the controller is nominal performance subject to signal constraints and robust stability with respect to a one-norm bounded model uncertainty.

Stability and feasibility in the absence of model uncertainty are studied for the nominal model and robust (feasible) performance is considered in the presence of additive uncertainty and input constraints on a stable plant. The extension to a general uncertainty types and constraints on states and output signals is done by considering the standard predictive control problem [30].

5.4 Predictive control of non-linear systems in the process industry

Project members: H.H.J. Bloemen, T.J.J. van den Boom, J.M.A. Scherpen, M.H.G. Verhaegen, V. Verdult, H. Oku, H.B. Verbruggen

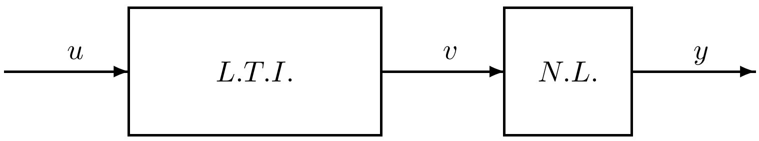
Sponsored by: STW

The project aims at the development of methods that enable to transfer the high investment return of currently used Model-based Predictive Controller (MPC) schemes for linear systems to important classes of nonlinear systems in the process industry.

* The first class contains systems which can, from an input-output point of view, accurately be described by a linear dynamical model when the operating range of the system is limited. Though, the present generation of MPCs are designed for this limited operating range, the tendency to produce more client oriented, will cause the processes to frequently make a transition from one limited operating range to the next. Using existing MPC technology these transient effects are not taken into account, possibly leading to non-smooth transitions and therefore economical losses.

* The second class contains processes that even for a limited operating range demonstrate a nonlinear behavior.

An example is a high purity distillation column which for a particular operating range can accurately be described by a series connection of a linear time invariant (L.T.I.) dynamic model followed by a static nonlinearity (N.L.), a so called Wiener model:



The special way in which the nonlinearity enters the Wiener model can be exploited by transforming it into uncertainty. The result will be an uncertain linear model, which enables to use robust linear MPC techniques [9, 10]. A high purity distillation column simulation model is used as a benchmark to test identification [12] and MPC algorithms [8] for Wiener systems.

A similar MPC approach has been developed for Hammerstein systems, in which a linear dynamic block is preceded by a static non-linearity [11].

A next extension towards more general nonlinear models will be the class of bilinear models, in which the non-linearity enters the dynamic part of the model.

This project is done in corporation with the University of Twente, Applied Physics, and is part of STW-project DEL 55.3891.

5.5 Model predictive control for discrete event and hybrid systems

Project members: B. De Schutter, T.J.J. van den Boom

Model predictive control (MPC) is a very popular controller design method in the process industry. An important advantage of MPC is that it allows the inclusion of constraints on the inputs and outputs. Usually MPC uses linear discrete-time models. In this project we extend MPC to a class of discrete event systems. Typical examples of discrete event systems are: flexible manufacturing systems, telecommunication networks, traffic control systems, multiprocessor operating systems, and logistic systems. In general models that describe the behavior of a discrete event system are nonlinear in conventional algebra. However, there is a class of discrete event systems – the max-plus-linear discrete event systems – that can be described by a model that is "linear" in the max-plus algebra.

We have developed an MPC framework for max-plus-linear discrete event systems [18, 19]. In general the resulting optimization problem is nonlinear and nonconvex. However, if the control objective and the constraints depend monotonically on the outputs of the system, the MPC problem can be recast as problem with a convex feasible set. If in addition the objective function is convex, this leads to a convex optimization problem, which can be solved very efficiently.

Recently we have extended these results to discrete event systems and hybrid systems that can be described by models in which the operations maximization, minimization, addition and scalar multiplication appear [17] (see also Project 3.1).

Topics for future research are the extension of the current MPC framework to nondeterministic max-plus-algebraic models, the development of efficient methods to solve this extended problem, a thorough investigation of the effects of the tuning parameters in max-plus-algebraic MPC, and determination of rules-of-thumb for selecting appropriate values for the tuning parameters.

5.6 Time wave form replication in the SCOOP project

Project members: J.M.A. Scherpen, G. Monsees

Sponsored by: European Union

The Brite Euram Seat COmfort Optimisation Procedure (SCOOP) project is a project in collaboration with European car manufacturers (BMW, Renault, IVECO), European car seat manufacturers (Faurecia, Lear), European universities (Seram Paris, University of Sheffield, Delft University of Technology), and has as program leader the Belgian company Leuven Measurement Systems (LMS).

The main objective of this RTD project is to develop a Seat Vibrational Comfort Testing procedure (SVCTP). The reason for proposing this RTD project is that few test procedures currently exist in industry, and no international standards define a complete procedure. Fundamental issues such as how to choose mission signals, how to treat the complex behavior of the person/seat system and how to choose human test subjects are completely lacking from all existing national and international standards. Vehicle and seat system manufacturers currently cannot compare test results obtained by different laboratories or exchange data. This situation is economically damaging because it adds large additional costs to vehicle and seat development programs by eliminating chances for concurrent engineering.

In the Control Laboratory (recently also in collaboration with the University of Twente) we develop a procedure to replicate the road signal that influences the movement of the car seat via the car. This is done in several steps. First an extension of the linear subspace identification procedure coping with nonlinearities of interest is applied in order to obtain a model of the car. The model that is obtained is then inverted by a newly developed stable dynamic model inversion technique in the feedforward loop in order to replicate the road signal. Then a compensation for the occurring errors is implemented in a feedback loop, using sliding mode control as a robust control technique. In relation to the latter, a new adaptive gain for the sliding mode control law is developed. The research is performed in close collaboration with the partners from LMS, Leuven, Belgium, and aims at implementation of the procedure at the experimental test facility of the car seat manufacturer Faurecia in France.

5.7 Nonlinear control of magnetic bearings

Project members: J.B. Klaassens, J.M.A. Scherpen

Magnetic bearings introduce the possibility of frictionless movements in the horizontal plane in deployment rigs for for example solar arrays. The bearings consist of electromagnets that are suspended underneath iron rails. A study is established to the control dynamics of magnetic levitation powered by a voltage source or current source. To stabilize the position of the magnet, nonlinear control techniques are applied, i.e. sliding mode and nonlinear PD are considered. An experimental magnetic levitation device is used to verify the results in analysis and simulation. The study is performed in cooperation with Fokker Space B.V. See [25] for published results of this research.

5.8 Nonlinear control systems analysis

Project members: J.M.A. Scherpen, K. Fujimoto, in collaboration with W.S. Gray, Virginia, USA

Sponsored by: NATO (partly)

This research focuses on extensions of linear realization theory to nonlinear control systems. The relation between input-output systems, Hankel operators, state-space realizations, minimality, and balanced realizations is considered. These considerations are important for applications to model and controller reduction, numerical efficiency, nonlinear black box identification and order estimation, sensor and actuator placements, etc.. A sequence of papers in this direction has been published, and a combination of those can be found in [23].

The study towards the relation of Hankel operators, its factorization in an observability and controllability part, and their state-space realizations, has given rise to a generalization of the notion of Hilbert adjoint systems to the nonlinear case. This topic uses concepts from physical systems, namely, Hamiltonian systems and their extensions, Legendre transformations, etc.

For several applications, it is also important that the physics of the system is taken into account. Here, we have a relation with the topics from the Physical Modeling and Control theme. Methods have been developed that consider the energy in Hamiltonian and Lagrangian systems, and use it for analysis and order reduction of these type of systems. So far, a limited amount of Hamiltonian and Lagrangian systems fit into the framework (i.e., systems with strictly positive potential energy), and we aim at extensions towards more general physical systems.

In order to make the above theory applicable for for example model reduction, the balanced model reduction procedure has been applied to a BOSCH SCARA robot that was available in the laboratory. A comparison of several model reduction methods, including a modification that takes the physics into account, has been performed. Furthermore, tools are being developed for solving partial differential equations that occur in many of these problems.

5.9 Model and controller reduction for nonlinear systems

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In almost all branches of engineering — e.g., mechanical, electrical, electronic, control and chemical — there has been a strong tendency to increase the complexity of the systems and the mathematical models. This has improved the precision on the prediction capacity of the models but also has made it more difficult to analyze them. With this, the study of methods to synthesize a compact model that concentrates on the essential properties of a bigger one, is becoming more important. This is known as "model reduction". Most of the time, model reduction has been accomplished based on the physical intuition of the analyst and her/his knowledge of the system's physical behavior. This usually results in a non-systematic, sometimes uncertain reduction procedure. A procedure to approximate a high order model by a lower order model should cope with the following issues.

1. The reduced order model has to capture the more important properties needed for the analysis. This properties may be time or frequency behavior, energy contribution, closed loop stability, etc.

2. It has to have a quantifiable small error estimate between the full order and the reduced order models, and admit different degrees of model reduction depending on the admissible error bound.

3. It has to be implementable in an (efficient) algorithm.

The study of systematic tools for model reduction of dynamic systems has been an early topic of interest in the systems and control fields. In the analysis of linear systems Kalman's minimal realization theory has shown to be an important tool to understand the system's structure, but for application purposes a lot of additional considerations are necessary due to its high sensitivity to parameter variations. On the other hand, optimal model approximation based on the Hankel norm and the balancing method have shown to be useful tools for model reduction. Today, singular-value-based balancing, LQG balancing, coprime factorization and H-infinity balancing are important practical tools for linear model reduction. For this reason the study of model reduction for linear systems can be considered a mature topic.

For nonlinear systems, there has been important progress with the nonlinear extensions of the systematic methods of balancing (singular-value-based, LQG and H-infinity) and coprime factorizations, mainly based on energy functions. These methods yield adequate procedures for nonlinear model reduction, but need to become more efficient and applicable.

Thus, the main purpose of this research consists in the development and refining of new tools for model reduction for nonlinear systems based on the state of the art nonlinear balancing theory. This research may have some close connections with discrete-time nonlinear systems and its identification procedures.

The results derived of this research should be extremely useful in a wide variety of applications in engineering.

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