Delft Center for Systems and Control
Research Report
2005

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1 Introduction

1.1 Overview

Delft Center for Systems and Control (DCSC) coordinates the education and research activities in systems and control at the Delft University of Technology. DCSC has been established in 2003 by merging the systems and control groups of Electrical Engineering (ITS), Mechanical Engineering (OCP) and Applied Physics (TNW).

The core research activity of the DCSC is twofold:

- the development of new theories and numerical tools for modeling and control of dynamic systems, and
- the validation of these new contributions in engineering applications.

The deliberately selected integration of the fundamental research line with the application oriented one, creates the ideal platform to systematically address problems in emerging technologies and to stimulate the development of innovative industrial control technology. The fundamental research activities concentrate on the three major areas of model based control design, i.e.,

- modeling
- system identification
- controller design.

The application oriented research aims at the adaptation and integration of fundamental innovations in laboratory demonstrations and for industrial pilot plants covering the following target application domains:

- industrial process control
- mechatronics and micro systems
- traffic and transportation control
- physical imaging systems.

The research activities in these domains are multi-disciplinary in nature and for the first 3 domains are defined in concurrence with the “Speerpunt” programs of Delft University of Technology.

1.2 Address and location

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2 Modeling

The models for designing controllers are primarily developed based on rigorous first principles on the laws of nature. Such models and related numerical solvers play an increasingly dominant role in virtual prototyping of new cars, industrial plants in the process industry, etc. The scientific challenge is the appropriate complexity reduction to make the overall optimisation of the plant design feasible. Contributions towards this challenge include the modeling of processes by large-scale first principles models and the use of measurement data for quantifying the dynamically relevant properties of non-linear chemical/physical processes in view of process monitoring, detection, (re)design, control and optimisation, as well as the development of model reduction and model uncertainty qualification tools for large scale industrial processes, that make a trade off between performance and computational efficiency tractable.

2.1 Model reduction of port-Hamiltonian fluid dynamics

Project members: R. Lopezlena, J.M.A. Scherpen

Sponsored by: Instituto Mexicano del Petróleo

Fluid Mechanics is one of the cornerstones of engineering. Through the fluid dynamics equations: continuity, momentum and energy; it is possible to model with fair precision a high variety of engineering problems. Especially due to the advances of *Computational Fluid Dynamics* (CFD) engineers could take full advantage of this theory. Applications of CFD can be seen customarily in the aerospace, the petroleum and others industries. Nevertheless, traditionally these models could not be used for real-time control purposes due to the high dimension of the systems and the high computational demand of the corresponding algorithms. In order to deal with these high dimensional models and to adapt them for analysis and control purposes *model reduction* tools have to be further developed.

Over the years some techniques for model reduction of fluids have been developed, but still the necessary order reduction is mainly done by physical insight and experience or with empirical methods (e.g. Karhunen-Loève expansion) which may provide accurate models but fail to provide a reduced model interpretable in physical terms. Since physical conceptualization of results is important, there is a need for a more systematic approach which preserves the physical structure in the reduced system.

A fairly general approach to model physical phenomena with control purposes is known as the *Port-Hamiltonian approach* which has been useful to describe the dynamic behavior of a very diversified class of engineering systems, including mechanical and electrical, resulting in a structured representation of possibly nonlinear differential equations. Recently in the literature, the extensions of this theory to distributed parameter systems — including fluids, — were formalized, providing with this a uniform and structured representation of the dynamic behavior of physical systems.

The method based on symmetries can be used for reduction of Hamiltonian systems. Though very formal and general, it fails to be applicable for control engineering purposes due in part to the fact that important input-output control concepts, like controllability and observability, were not considered in their formulation.

During the course of this research we have shown that the Dissipativity Theory provides a very general framework to deal with the input-output control properties while preserving the physical structure of the system. Moreover, based on this theory several successful control algorithms can be used.

Based on the framework of Dissipativity Theory and the resulting models from the Port-Hamiltonian paradigm in fluids, the main objective of this research lies on the design of structure-preserving nonlinear balanced reduction algorithms.

2.2 Nonlinear control systems analysis

Project members: J.M.A. Scherpen, W.S. Gray (Virginia, USA), K. Fujimoto (Kyoto, Japan)

Sponsored by: NWO

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.

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. Based on these methods, a procedure towards a new balancing method for nonlinear system is defined, resulting in a procedure for model reduction that is part of the on-going research. So far, a constructive algorithm is part of the procedure, which aims at the development of implementation tools.

2.3 Relating Lagrangian and Hamiltonian descriptions of electrical circuits

Project members: J. Clemente Gallardo, J.M.A. Scherpen, D. Jeltsema

In the last years, an evident interest for the Lagrangian and Hamiltonian description of electrical circuits has arisen in the literature. A recent Lagrangian description [29, 30] leads to a successful picture of RLC circuit dynamics and provides a step-by-step construction for the description of the components, the definition of the Lagrangian, and the corresponding Euler-Lagrange dynamics. Kirchhoff's current law defines a set of holonomic constraints for the corresponding Lagrangian system, while the corresponding voltage law defines the Euler-Lagrange equations for the system. Regarding the Hamiltonian description of the dynamics of electrical circuits, a recent and successful approach is based on the concept of Dirac structures and port-controlled Hamiltonian systems. This approach also provides a suitable description of the dynamics of the system.

It seems quite natural to compare both approaches and to try to relate the solutions of both methods for electrical circuits. Since dissipative elements and sources can be viewed as external elements, we only consider electrical LC circuits here. The formulation of both frameworks is done in R^n and hence the canonical procedure would suggest to use the Legendre transform to go from dynamics given by the Lagrangian formalism into dynamics given by the Hamiltonian formalism, and vice versa. The problem in this case is that the Lagrangian formalism proposed in [29, 30] yields a singular Lagrangian description, which makes the

Legendre transform ill-defined and thus no straightforward Hamiltonian formulation can be related. We complement the original Lagrangian picture proposed in [29, 30] with a procedure that transforms the singular Lagrangian system into a regular Lagrangian system. Then the Lagrangian system can be related with a Hamiltonian system by using a well defined Legendre transform. The main new ingredient of the approach is the use of Lie algebroids in the description. A Lie algebroid is a geometrical object which generalizes the concept of tangent bundles (which is the natural framework of usual Lagrangian mechanics) such that a Lagrangian formulation on them is still possible. Essentially, we just need one of the simplest examples of the Lie algebroid, namely an integrable subbundle of a tangent bundle, which in the case of electrical LC circuits is even a vector space. For the case of networks without switches, this approach is equivalent to use the integrated version of Kirchhoff current law. This implies the use of the condition of charge conservation, to define a regular Lagrangian description by using only the inductances of the system.

The future research includes the extension of the new framework to more general circuits, including switched networks, and to merge this approach with the extension of Brayton-Moser equations.

2.4 Modeling and analysis of hybrid systems

Project members: B. De Schutter, W.M.P.H. Heemels (Eindhoven University of Technology), A. Bemporad (ETH Zürich)

Sponsored by: SICONOS (EU project)

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 1).

We have shown that several classes of hybrid systems: piecewise-affine systems, mixed logical dynamical systems, complementarity systems and max-min-plus-scaling systems are equivalent [3, 4, 22, 23]. Some of the equivalences are established under (rather mild) additional assumptions. These results are of paramount importance for transferring theoretical properties and tools from one class to another, with the consequence that for the study of a particular hybrid system that belongs to any of these classes, one can choose the most convenient hybrid modeling framework. Related research is described under Project 4.9.

In addition, we have also shown an equivalence between two type of mathematical programming problems: the linear complementarity problem (LCP) and the extended linear complementarity problem (ELCP) [14]. More specifically, we have shown that an ELCP with a bounded feasible set can be recast as an LCP. This result allows us to apply existing LCP algorithms to solve ELCPs [13].

2.5 Model based optimization of fed-batch bioprocesses

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

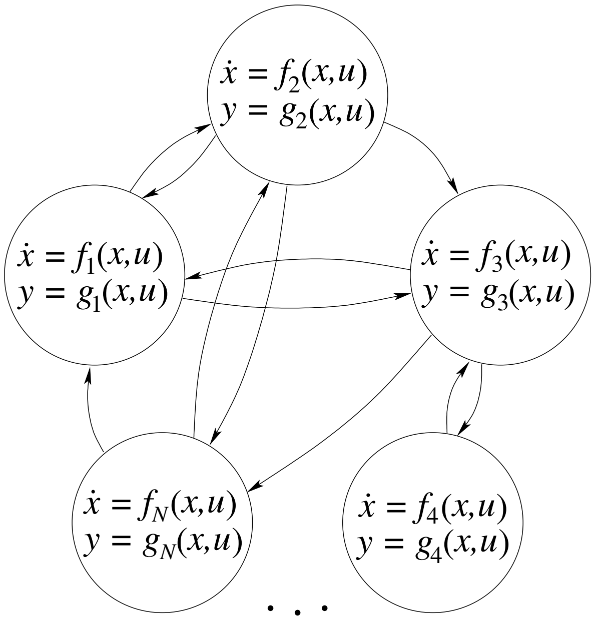

Figure 1: Schematic representation of a hybrid system.

Sponsored by: DSM Anti Infectives, DIOC-6

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. 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. 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 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 initial 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. The results of this research are reported in the Ph.D. dissertation by J.A. Roubos.

3 System identification

When an actual plant exists, the problem of developing a model for a model based controller is addressed primarily based on the signals acquired from the plant to be controlled. In the development of solutions for such identification problems research is conducted along 3 different approaches:
First, the intelligent modeling approach. Intelligent methodologies employ techniques inspired by the functionality of intelligent biological systems.
Second, to improve the user interaction and performance of identification methods novel techniques for specific classes of linear, non-linear and hybrid systems are developed.
Third, the key question in identification for control is the development of low order models based on the design of appropriate experimental conditions and closed-loop system identification techniques. Considering applications with arrays of thousands and thousands of sensors (MEMS) and actuators the analysis paradigm is shifted from centralized processing methods towards decentralised ones.

3.1 Model based monitoring of large scale processes in process industry

Project members: R. Bos, P.M.J. Van den Hof, X.J.A. Bombois

Sponsored by: TNO-TPD

In process industry a lot of time and effort is spent on modelling large scale processes using first principles relations. The resulting models usually consist of a large set of non-linear partial differential equations. These equations usually cannot be solved analytically, which means they have to be solved numerically on a fine spacial grid. The models can be converted to the familiar state-space form by assigning one or more states to each point on the spatial grid. Solving the equations on this grid tends to be computationally intensive.

Before we can use these first principles models for monitoring purposes, we face three main problems. The first problem is that the number of states in the model is often very large. A second problem is that the state-equations are very computationally intensive. The final obstacle is that these first principle models tend to be non-linear. These difficulties cause that standard solutions to monitoring, such as Kalman filtering cannot be used. In this project we will attempt to find alternative strategies for monitoring process variables.

The methods and techniques developed in the project are tested in a case study. The case study in this project consists of a dynamic model of the dryer section of a paper mill, see Figure 2.

This research is being done in cooperation with the Control Engineering and Process Physics groups of TNO-TPD in Delft.

3.2 Towards experiment-based robust control design

Project members: X.J.A. Bombois, P.M.J. Van den Hof, M. Gevers (Université Catholique de Louvain, Belgium), G. Scorletti (Université de Caen, France), B.D.O. Anderson (Australian National University and National ICT Australia, Australia), P. Date (Brunel University, United Kingdom)

Feedback control has nowadays reached many industrial sectors (chemical industry, elec-

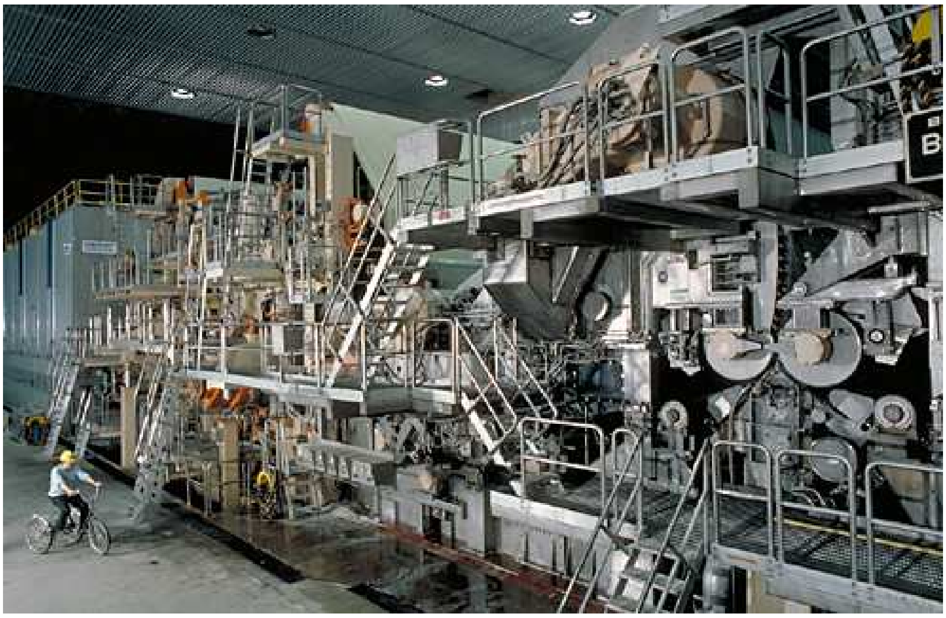

Figure 2: Paper mill.

tronic devices, high tech manufacturing industry) since this technology allows one to meet the requirements of modern industry i.e. quality, performance and optimal process operation. However, the development of feedback control is still restrained by various open issues in control and system theory. In most of these issues, the harmonious interaction between modelling (or system identification) and model-based robust control design is very important.

The control engineer often faces the problem to obtain a model and a description of the model uncertainty that are not compatible with the techniques developed for robust control design. In order to improve the design of feedback loops, the efficient connection of system identification and robust control design is thus of the highest significance and relevance. This connection must lead to an experiment-based robust control design procedure i.e. a robust control design procedure which uses the model and its related uncertainty as delivered by system identification.

Since the beginning of the nineties, many efforts have been spent in this direction. The methodology that has been developed so far can only be applied for a limited class of systems. For the practical implementation of this methodology, it is necessary to extend this class to multivariable systems with non-linear dynamic components. This extension to multivariable systems and to certain classes of non-linear systems (e.g., NARMAX systems or systems with a small non-linearity) is one objective of our research project. Besides, the very present issue of optimal experiment design also plays a very important role in our research project. The objective of optimal experiment design is to determine the less costly identification experiment that delivers sufficient information on the system dynamics for the design of a robust controller.

3.3 Identification of hybrid systems

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

Hybrid models consist of a combination of continuous dynamics (differential or difference equations) and discrete dynamics (discrete-events, logical switches, automata). They form an important class of dynamical systems for which analysis, verification and control techniques have been widely studied. However, identification techniques for hybrid systems have not received a lot of attention.

The goal of this research is to develop identification techniques for several classes of hybrid systems. The identification techniques will be based on our experience with state-space identification methods for linear and nonlinear systems, especially the subspace type of methods. Identification methods will be developed that determine a discrete-time multivariable state-space model using input and output measurements We have performed some preliminary work on the identification of hybrid systems that can be described by max-plus-linear discrete event systems.

3.4 Bounding uncertainty in subspace identification

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

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

In the recent years, subspace model identification (SMI) has become a popular tool for the identification of state-space models under the influence of disturbances. The fully parameterized state-space is estimated using robust and accurate subspace model identification methods, such as CVA, MOESP and N4SID. 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 described in [37] and [38] 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. All three mentioned subspace identification algorithms (MOESP, N4SID and CVA) can be handled by the above method, since the three algorithms are closely related.

3.5 Identification of nonlinear state-space systems

Project members: V. Verdult, M. Verhaegen

Over the years considerable attention has been given to the identification of linear systems. Linear systems have proven their usefulness in numerous engineering applications, and many theoretical results have been derived for the identification and control of these systems. However, most real-life systems inherently show nonlinear dynamic behavior. Consequently, the use of linear models has its limitations. When performance requirements are high, the linear model is no longer accurate enough, and nonlinear models have to be used. This motivates the development of identification methods for nonlinear systems.

In this project, new system identification methods are developed for nonlinear state-space systems. Although most work on nonlinear system identification deals with nonlinear input-output descriptions, state-space systems are considered, because they are especially suitable for dealing with multiple inputs and outputs, and they usually require less parameters to describe a system than input-output descriptions do. Equally important, the starting point of many nonlinear control methods is a state-space model of the system to be controlled. Currently, identification methods have been developed for three particular types of nonlinear systems: linear parameter-varying state-space systems, bilinear state-space systems, and local linear state-space systems.

3.6 Development of computationally efficient and numerically robust system identification software

Project members: V. Verdult, M. Verhaegen

Over the years several methods for system identification of multivariable linear state-space systems have been developed. To make these methods available to a large community of scientist and engineers in both industry and academics, a reliable and efficient implementation of these methods is needed. The goal of this work is to develop a software package that provides computationally efficient and numerically robust implementations of several system identification methods for multivariable linear state-space systems. The software is developed for use with Matlab and is partly written in the C programming language. It makes use of numerical linear algebra routines from BLAS, LAPACK, and SLICOT.

The software development focuses on the following identification methods: 1) time and frequency domain subspace methods, 2) state-space system identification based on minimizing the prediction error, and 3) state-space system identification by fitting frequency response functions.

3.7 Choice of uncertainty structure in identification for robust control

Project members: S.G. Douma, P.M.J. Van den Hof

In identification for robust control an identified model has to be accompanied by a bound on its uncertainty, while the representation of this uncertainty should allow for robustness analysis and robust controller synthesis. A large number of such uncertainty descriptions is available from robust control theory, as e.g. a (H_∞)-norm-bounded additive or multiplicative uncertainty on the plant model, a norm-bounded uncertainty on a closed-loop plant representation (e.g. its dual Youla parameter), uncertainties bounded in the gap or ν-gap metric, and real parametric uncertainties. On the other hand, a range of identification techniques exists providing for uncertainty structures identified from the data, as e.g. parametrically structured (ellipsoidal) uncertainty, norm-bounded additive, non-parametric (boxed, ellipsoidal) additive in the frequency domain. Amongst such a variety of possible uncertainty structures a relevant

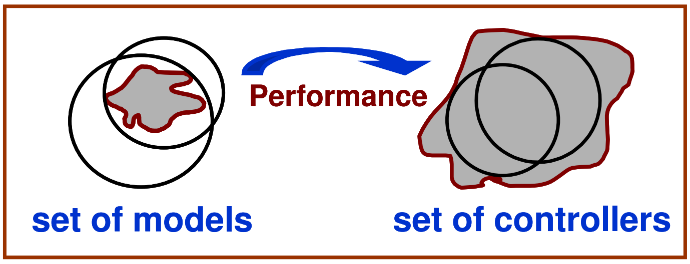

Figure 3: Uncertainty structure and robust control.

question is what the implications are of a particular choice of structure in the identification for robust control problem.

An ultimate question to be answered would be what is, for a given purpose (robust stability/performance analyis or synthesis), the best model uncertainty structure in which to identify the model set (nominal model and uncertainty bound). And consequently, what would be the best experiment allowing for minimisation of the uncertainty.

While extensive literature exists dealing with characteristics of each uncertainty structure, answering the posed question requires a thorough comparison and a bridging of the gap between identification and robust control that goes beyond the present state of the art. This project is intended to highlight aspects in which the various uncertainty structures differ in their consequences for robust analysis and design and in their potentials to be determined on the basis of realistic experimental data.

3.8 Multi-objective nonlinear identification

Project members: R. Babuška, K. Maertens (Katholieke Universiteit Leuven), T.A. Johansen (Norwegian University of Science and Technology)

Sponsored by: Fonds voor Wetenschappelijk Onderzoek in Vlaanderen

Methods for the multi-objective identification of nonlinear dynamic models consisting of local linear models are being investigated. The tradeoff between global model accuracy and interpretability of the local models is explicitly considered by introducing weights on the criteria for local model accuracy. A strategy has been proposed to tune the local weights in order to achieve a similar tradeoff for each local model. In this way, the model generalization is improved. The multi-objective identification algorithm has been applied to predict the engine load of an off-road vehicle (a combine harvester) operating under varying working load conditions. The analysis tools have proven useful for the construction of an accurate and robust engine load prediction model. The resulting model can directly be used in model-based control algorithms in automatic tuning systems that explicitly deal with constraints on the working region.

3.9 System identification of bio-technological processes

Project members: M. Verhaegen, H.H.J. Bloemen (Biotechnology, Delft University of Technology)

The purpose of metabolic modeling is, in the first place, to understand the in vivo kinetics

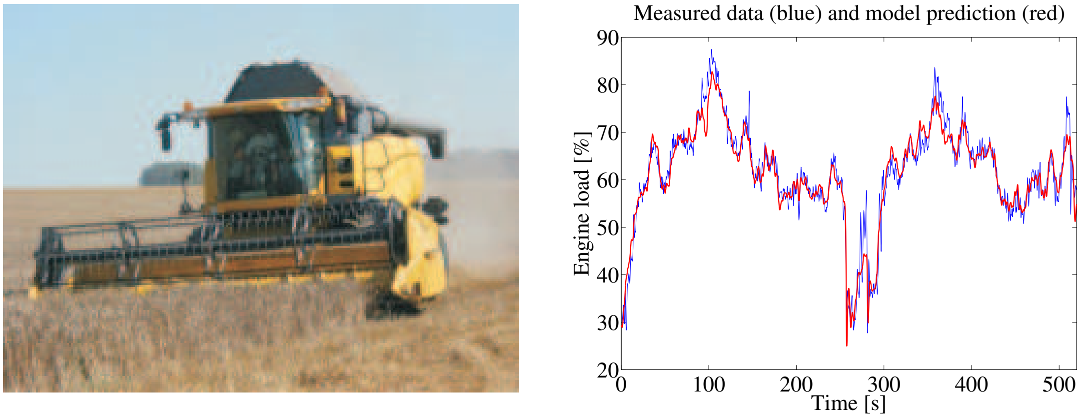

Figure 4: Multi-objective nonlinear identification was used to construct a model to predict the engine load of a combine harvester.

of the metabolism of a (micro) organism, and in the second place, to possibly reprogram this metabolism. The models often describe the metabolism under the assumption that the amount of enzymes remains constant, e.g. [27]. Both to reveal the metabolism and to verify the metabolic models, pulse experiments are conducted to a steady state culture of the particular organism. In order to be able to neglect the biosynthesis of new enzymes, the data should be collected within a time window of a few minutes after the pulse. This motivates the development of rapid sampling techniques to analyze the dynamics of the different metabolites in this time window (see, e.g., [31]). Besides, often measurements are available of the oxygen O_2 and carbon dioxide CO_2 concentrations in the off-gas of a fermenter, measured by a gas analyzer, and of the dissolved oxygen (DO) concentration in the fermentation broth.

The latter measurement can be used to reconstruct the dynamics of the oxygen uptake rate (OUR) and carbon dioxide evolution (CER) after the pulse, and in turn can be used to analyze the metabolism and to verify the metabolic models. To reconstruct the OUR and CER first a model is required that describes the dynamic relation between the OUR and CER (the impulse of the model) and the measured quantities provided by the gas analyzer and the DO sensor (the outputs of the model). Using this off-gas model, the OUR and CER can be reconstructed from the data (collected during the pulse experiment) by using estimation techniques.

3.10 Classification of buried objects based on ground penetrating radar signals

Project members: M. Verhaegen

Ground Penetrating Radar (GPR) is widely used for the non-invasive investigation of the subsurface and man-made structures. Applications include utility location, landmine and unexploded ordinance detection, road inspection, mapping of groundwater contamination, archeology, etc. Especially for landmine detection the interest in GPR has grown significantly over the last 5 years. This is the result of increased awareness about the severity of the global landmine problem (see, e.g., `http://www.oneworld.org/guides/landmines/index.html`) as well as the advantages that GPR has to offer over other sensors such as metal detectors.

These advantages include the capability to detect both plastic and metallic landmines.

Currently, an extensive GPR research project is carried out at the International Research Centre for Telecommunications-Transmission and Radar (IRCTR) in cooperation with the Control Systems Engineering group, the section of Applied Geophysics and the Laboratory of Electromagnetic Research. The project encompasses a variety of research activities aimed at improving landmine detection with GPR. These include the development of ultra-wideband GPR systems and new data processing schemes such as imaging, inversion and classification, to name a few. The research in collaboration with the Control Systems Engineering group falls into the area of object classification.

3.11 Identification and control of LPV systems using orthonormal basis functions

Project members: P.M.J. Van den Hof, C.W. Scherer, V. Verdult, P.S.C. Heuberger, R.T. Tóth

Sponsored by: NWO

Orthogonal basis functions have a long history in the context of system approximation and identification. Examples are the standard pulse basis and the Laguerre basis. These are both special cases of a more general construction in which the basis functions are generated by a cascaded network of all-pass filters. Typically basis function models are parameterized as

$$G(z) = \sum_{k=1}^{n} c_k \phi_k(z) \ ,$$

where $\{\phi_k(z)\}$ denotes the set of basis functions and $\{c_k\}$ is the set of coefficients (parameters). An important advantage of this parameterization is that the model parameters appear linearly (this implies that in least squares settings the optimum is unique and easily calculated). Furthermore it leads to an output error structure (consistent estimation of the transfer function, irrespective of noise). This project aims at the exploration of the possible advantages of orthogonal basis functions for the modeling and control of non-linear systems.

Many practical (control) systems involve phenomena that are not only functions of time, but also of other independent variables, such as, e.g., space coordinates. Furthermore, these functions are sometimes nonlinear and/or non-stationary. As a result the accurate modeling of such systems is in general a complex and tedious task, involving the use of nonlinear partial differential equations, leading to models with a huge number of parameters and high computational complexity. On the other hand accurate and efficient control of the relevant process variables is of paramount importance to satisfy the increasing performance demands. In order to achieve these goals, control algorithms and methods have to be applied that require process models of low complexity. This project aims at the development and application of a new generation of tools for identification and control of these processes, enhancing results recently obtained in systems and control theory, with the goal to bridge this obvious gap between modeling and control requirements by the creation of relatively simple models, that are both accurate in the representation of the overall system behavior, suited for control design. One of the approaches taken will consist of interpolation of locally linear models, combining the theory on LPV (linear parameter varying) systems and the theory on orthogonal basis functions.

4 Controller design

The fundamental question of taking uncertainty of the model in the design of high performance centralised or decentralised controllers into account is addressed from a large number of different ways: (1) Physically structured controllers in correspondence with the structure of the system to be controlled are investigated based on the Lagrangian and Hamiltonian framework and on energy control, (2) Optimisation based on e.g. semi definite programming is investigated for multi criteria robust controller design, (3) Fault tolerant controller design methods are developed that are able to detect and to modify the controller settings before a fault turns into a failure or catastrophe. (4) Model predictive control for classes of hybrid systems, etc.

4.1 Theory and design of robust control systems

Project members: C.W. Scherer

Modern controller design techniques are based on models of a physical plant which are obtained using first principles or system identification. It is often possible to incorporate predictable changes of the physical plant into a model, such as variations in measurable parameters. In addition, one might as well encounter unpredictable or unmeasurable plant variations or system parts which are hard if impossible to be approximated by simple models. In order to cope with the latter effects, it is hence reasonable to base the controller design on a whole set of models which can be parameterized in a simple fashion. Combining both uncertainty structures, any realistic control design methodology should hence start with a parameterized family of model sets, the parameter capturing the measurable changes of the plant and the model sets representing unpredictable system variations. The design algorithm should lead to a parameterized or scheduled family of controllers which achieves not only one but a variety of design objectives for all elements in the model set.

Performance objectives are either specified in a qualitative manner (regulation, disturbance decoupling) or they can be quantified using system norms or gains (with the H_2-norm and H_∞-norm as typical examples). For linear time invariant systems, it is by now well-established how to solve many of these problems independently. However, the theory of designing controllers achieving multiple objectives for one model or for a whole model set, the so-called robust multi-objective design, is still in its infancy.

The main goal of our research is to push further new developments in the area of robust multi-objective control and to combine the corresponding controller synthesis with scheduling techniques if the system varies with a measurable parameter.

4.2 Efficient analysis and synthesis tools for robust and scheduled controller design against time-varying and dynamic uncertainties

Project members: S. Dietz, C.W. Scherer

In recent years optimization based robust controller analysis and synthesis techniques have emerged as powerful tools in numerous practical control applications. In particular the development of fast optimization algorithms for solving semi-definite programming problems during the last decade has caused a paradigm shift in control to handle design problems that are deemed untractable with established analytical techniques. Despite impressive progress, it is only partially understood how to effectively incorporate mixtures of dynamic time-invariant and rate-bounded time-varying uncertainties into systematic controller analysis and synthesis algorithms by employing suitable relaxation schemes, and it is largely unexplored how to estimate relaxation errors.

This project aims at developing an integrated theoretical framework for handling uncertainty mixtures by merging time- and frequency-domain descriptions of their properties. Emphasis will be put on the development of structure exploiting numerical algorithms that allow a gradual reduction of relaxation errors and that generate bounds on the involved conservatism. This fundamentally novel strategy leads to the second goal, the development of the corresponding robust and scheduled controller synthesis techniques, with the demonstration of their applicability for regulating systems whose dynamics vary with time or nonlinearly. These schemes will involve a partition of uncertainty value sets such that robust or scheduled controller design will be intimately related to the design of multi-objective and switched controllers for a large number of models. The third goal is to arrive at a fundamentally new understanding of the interrelations of these topics with the design of structured controllers for system network interconnections.

4.3 Robust model predictive control

Project members: H. Chen (Jilin University), C.W. Scherer

Model predictive control (MPC) is among the most successful regulation techniques in process industry. As the essential theoretical benefit, MPC achieves feedback-control action by solving open-loop optimization problems on-line. Industrial systems typically suffer from a large plant-model mismatch which can lead to considerable performance degradation in on-line optimization schemes if not taken into account. Unfortunately the systematic incorporation of (structured) uncertainties in the MPC framework is still rather immature. The main goal of this research is to understand how feedback-control action can be generated for uncertain models by solving minimax problems for open-loop strategies.

As an initial step we specifically consider the L_2-disturbance attenuation problem with hard constraints on the control inputs. Based on game-theoretic techniques we investigate schemes that allow to relax or tighten performance specifications during on-line optimization in order to avoid input saturation while still guaranteeing desired performance specifications. Our ultimate goal is a non-conservative solution of the H_∞-synthesis problem with hard constraints.

4.4 Robust active control of noise and vibrations

Project members: P.R. Fraanje, M. Verhaegen

Our research on robust active control of noise and vibrations focuses on the suppression of broadband stochastic disturbances (see e.g. Figure 5). Until now active noise/vibration control (ANVC) has been successfully applied to cancel harmonic disturbances, e.g. in propeller aircrafts and air conditioning systems. In most of these ANVC systems, the Filtered-X LMS algorithm is applied, because of its simplicity and adaptivity.

However, the control of broadband disturbances, e.g. in jet aircrafts and road-tire/aerodynamic noise in cars, suffers to some important problems, which has hold back from practical application:

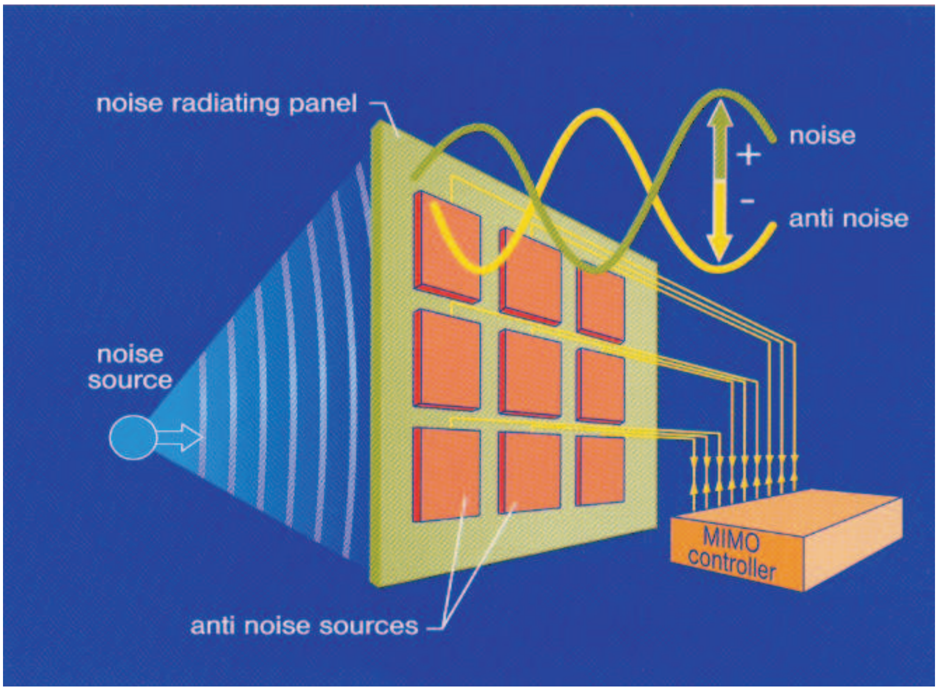

Figure 5: Artist impression of a smart panel system, in which disturbing vibrations are suppressed by controlling piezo-electric actuators.

- contrary to the case of harmonic disturbances, in the case of broadband disturbances usually no reference signal which is highly correlated with the disturbance is available;
- adaptive LMS algorithms, like Filtered-X LMS converges very slowly due to correlation in the broadband regression signal;
- the system to be controlled is usually an infinite dimensional system, which yields high model orders in its finite order approximation;
- the system, especially actuators and sensors, often suffer to nonlinear behavior.

To solve these problems, we have proposed two solutions:

1. an off-line probabilistic control design method, which optimizes the average performance over a stochastic model uncertainty set;
2. an robust fast adaptive control design method, which is basically a robust preconditioned version of the Filtered-X LMS algorithm.

Our research to improve the performance of the first method is on control-relevant (closed-loop) identification of the model and iterative identification and controller design. In cooperation with the University of California, Los Angels, we investigate how to improve the second method, such that performance bounds can be guaranteed.

For large scale applications, e.g. in smart materials, with many sensors and actuators, decentralized and distributed control methods needs to be developed to reduce the complexity of the real-time controller. Therefore a second main research goal is to design and practically validate decentralized ANVC algorithms for broadband disturbance suppression.

This project is done in cooperation with TNO-TPD.

4.5 On weight adjustment in H_∞ control design

Project members: X.J.A. Bombois, B.D.O. Anderson and A. Lanzon (Australian National University and National ICT Australia, Australia)

In recent years, H_∞ control design has become a well-known method to design a model-based controller satisfying a number of constraints expressed by amplitude bounds (weights) on the "to-be-designed" closed-loop transfer functions. This method has known numerous applications for control design on real-life systems. The design of a controller using H_∞ control design generally follows an iterative procedure. In a first step, only the sensitivity function is effectively constrained (i.e., the constraints on the other transfer functions are chosen in such a way that they remain ineffective). A first controller is obtained in this way. However, this controller has generally an unsatisfactory performance with respect to the closed-loop transfer functions for which the constraints were (in this first step) too loose to be effective. Consequently, in a second step, the weights on these closed-loop transfer functions are adapted in order to improve the closed-loop behaviour of the controller and a second controller is computed using these adapted weights. This procedure is pursued until the obtained controller is judged satisfactory enough. The way with which the weights are adapted at each "iteration" is generally purely heuristic. It is consequently very interesting to build some insights about the influence of a weight modification on the obtained (central) controller and, more importantly, on the obtained closed-loop transfer functions in order to be able to improve the way H_∞ control design is performed.

4.6 Discrete-time sliding mode control

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

Sliding mode control is a well known robust control algorithm for linear as well as nonlinear systems. Continuous-time sliding mode control has been extensively studied and has been used in various applications. Much less is known of discrete-time sliding mode controllers. In practice it is often assumed that the sampling frequency is sufficiently high to assume that the closed-loop system is continuous-time. Another possibility is to design the sliding mode controller in discrete-time, based on a discrete-time model of the sampled system under control.

State-based, discrete-time, sliding mode control has received quite some attention over the last decade. The main problem encountered in discrete-time sliding mode control, as opposed to continuous-time sliding mode control, is the limited switching speed. Where the switching frequency in continuous-time is assumed to be infinite, in discrete-time it is limited by the sampling frequency. Therefore (perfect) sliding mode can not be attained in discrete-time. Instead, the best achievable result is to steer the closed-loop system within a small boundary region around the switching surface called the quasi sliding mode band. As opposed to discrete-time state-based sliding mode control, discrete-time output-based sliding mode has received little attention. Research in this area has been focused on a transfer function approach so far.

Our research has been focused on the design of an output-based discrete-time sliding mode controller based on a linear state-space representation of the system. Using this method, the design of the output-based controller can be applied easily to MIMO (multiple input multiple output) as well. Further improvements are made by the use of disturbance estimation and reduced order state observation. It is also shown that the derived controller can be applied to the problem of target tracking, possibly in conjunction with a feedforward controller. Simulation studies demonstrate the applicability of the developed control theory.

4.7 Multi-agent control of large-scale hybrid systems

Project members: R. Negenborn, B. De Schutter

Sponsored by: STW & NWO(via the VIDI Innovational Research Incentives Scheme)

Huge traffic congestion after recent incidents (such as the bomb alerts in the tunnels in Amsterdam, or at the IKEA stores), or the problems in the US, The Netherlands, and Italy due to power outages have shown the crucial role of a reliable operation of traffic and transportation systems, electricity distribution networks, and other large-scale complex systems that are one of the corner-stones of our modern society such as water distribution, logistic operations, and telecommunication networks. A reliable and efficient operation of these systems is not only of paramount importance when the systems are pressed to the limits of their performance, but also under regular operating conditions. The systems mentioned above can be modeled as hybrid systems, i.e., systems with both continuous and discrete dynamics. A smooth, efficient and safe operation of these systems is of paramount importance for the economic growth, the environment, and the quality of life.

Up to now, most control methods for hybrid systems are based on a centralized control paradigm and/or on ad-hoc techniques. However, centralized control of large-scale systems is often not feasible in practice due to computational complexity, communication overhead, and lack of scalability. Furthermore, a structured control design method is also lacking. Therefore, we propose to develop a structured and tractable design methodology for robust control of large-scale hybrid systems.

In this project we will develop both the necessary *new theory* and a corresponding *design framework* for control of large-scale hybrid systems using an approach based on:

- a multi-level control structure with local "control agents" at the lowest level, and one or more higher "supervisory" control levels,
- combination and integration of techniques from computer science and control engineering in order to obtain coordination *at* and *across* all control levels.

This will result in systematic approaches that outperform existing heuristic or case-dependent decentralized control strategies.

In addition to performing fundamental research on control of large-scale hybrid systems, we will concentrate on three specific application fields: traffic & transportation, electricity distribution, and logistics.

4.8 Model predictive control for discrete-event 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 further developed our MPC framework for max-plus-linear discrete-event systems and included the influences of noise and disturbances [32, 33, 34, 35, 36]. In addition, we have also extended our results to discrete-event systems that can be described by models in which the operations maximization, minimization, addition and scalar multiplication appear [19], and to discrete-event systems with both hard and soft synchronization constraints [16] (see also Project 7.3).

4.9 Model predictive control for piece-wise affine systems

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

We have extended our results on model predictive control (MPC) for discrete event systems (see Project 4.8) to a class of hybrid systems that can be described by a continuous piecewise-affine state space model. More specifically, we have considered systems of the form

$$\begin{aligned} x(k) &= \mathcal{P}_x(x(k-1), u(k)) \\ y(k) &= \mathcal{P}_y(x(k), u(k)) \ , \end{aligned}$$

where x, u and y are respectively, the state, the input and the output vector of the system, and where the components of $\mathcal{P}_x$ and $\mathcal{P}_y$ are continuous piecewise-affine (PWA) scalar functions, i.e., functions that satisfy the following conditions:

1. The domain space of f is divided into a finite number of polyhedral regions;
2. In each region f can be expressed as an affine function;
3. f is continuous on any boundary between two regions.

We have shown that continuous PWA systems are equivalent to max-min-plus-scaling systems (i.e., systems that can be modeled using maximization, minimization, addition and scalar multiplication). Next, we have considered MPC for these systems. In general, this leads to nonlinear non-convex optimization problems. However, we have developed a method based on canonical forms for max-min-plus-scaling functions to solve these optimization problems in a more efficient way than by just applying nonlinear optimization as was done in previous research. More specifically, the proposed algorithm consists in solving several linear programming problems [20].

4.10 Model predictive control for hybrid systems

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

Sponsored by: STW

Both academia and industry have recently directed a considerable amount of research effort on hybrid systems. Hybrid systems typically arise when continuous plants are coupled with controllers that involve discrete logic actions. Although hybrid systems are encountered in many practical situations, up to now most controllers for such systems are designed using ad hoc and heuristic procedures. Due to the complex nature of hybrid systems, it is infeasible to come up with generally applicable control design methods.

In this project we will therefore focus on structured control design methods for specific classes of hybrid systems that are industrially relevant. These methods will be extensions of the model predictive control (MPC) framework for continuous systems, so as to include hybrid systems. The MPC scheme is nowadays very popular in the oil refining and (petrochemical) process industry and has adequately proved its usefulness in practice. MPC offers attractive features that makes this control approach also interesting and relevant for extension to hybrid systems. In this project we will develop high performance MPC controller design techniques for hybrid systems, concentrating on applications in the chemical process industry (Shell) and in the brewing industry (Heineken).

Currently, we have already obtained some initial results on MPC for special classes of hybrid systems (see Projects 2.4, 4.9 and 7.3). In this project we will further extend these results to more relevant classes of hybrid systems, thoroughly investigate and formalize the design process, improve optimization procedures to realize real-time implementation, and use the results for practical problems of the partners from industry.

This project is done in cooperation with dr. W.P.M.H. Heemels of the Control Systems group of Eindhoven University of Technology.

4.11 Predictive control of nonlinear systems in the process industry

Project members: H.H.J. Bloemen, T.J.J. van den Boom, J.M.A. Scherpen, M. 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

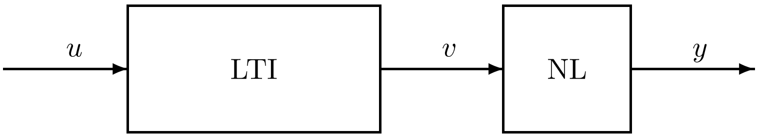

Figure 6: Block diagram of a Wiener model.

particular operating range can accurately be described by a series connection of a linear time-invariant (LTI) dynamic model followed by a static output nonlinearity (NL), a so-called Wiener model (see Figure 6).

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. A similar approach can be applied for Hammerstein systems, in which case a linear dynamic block is preceded by a static input nonlinearity. This Hammerstein-Wiener MPC algorithm [8] extends the linear MPC algorithm described in [10]. A case study, concerning the distillation column benchmark, has demonstrated the effectiveness of the proposed Wiener MPC algorithm and is presented in [7].

Also discrete-time bilinear models may be useful for black-box identification of nonlinear processes. In bilinear models the nonlinearity enters the dynamic part of the model, i.e. the state equation contains a product term between the current state and the current input. This property can be exploited for solving a "classical" finite horizon MPC problem [9]. An application of bilinear MPC to a polymerization reactor is presented in [12]. Extensions to an infinite-horizon bilinear MPC algorithm can be found in [5, 11]. Extensions to bilinear MPC algorithms that aim at a low computational demand for the on-line computations are reported in [6, 5].

This project is part of STW project DEL 55.3891. This project is done in co-operation with the Control group of the University of Oxford, UK.

4.12 Robust and predictive control using neural networks

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

The aim of the project is to investigate the possibilities of the application of neural networks to the predictive control of dynamical systems. It contains two sub-projects.

In the first sub-project we aim to establish a link between accuracy of function approximation with a neural network and the stability of the system, leading to 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. The project specifically investigates 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.

In the second sub-project investigate the use of neural networks in the design of analytic constrained predictive controllers for linear systems that combines constraint handling with speed and is applicable to control problems with many constraints. The solution to the model predictive control problem is a continuous function of the state, the reference signal, the noise and the disturbances and hence can be approximated arbitrarily close by a feed-forward neural network. This leads to an analytic constrained predictive controller that combines constraint handling with speed and is applicable to fast systems and complex control problems with many constraints [26, 1].

This project is done in co-operation with the IST group of the University of Lisbon.

4.13 The standard predictive control problem

Project members: T.J.J. van den Boom, A.C.P.M. Backx (Eindhoven University of Technology)

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 and infinite horizon predictive control problems can be seen as special realizations of this SPCP. The SPCP and its solution are given in state-space. The objective of the controller is nominal performance subject to signal constraints and robust stability with respect to bounded model uncertainty.

Stability and feasibility are studied for the finite and infinite prediction horizon case with structured input signals descriptions and level and rate constraints on input, state and output signals.

This project is done in cooperation with the Control Systems group of Eindhoven University of Technology.

4.14 Model-based fault detection and controller reconfiguration for wind turbines

Project members: V. Verdult, M. Verhaegen, S. Mešić

Sponsored by: Novem

Wind turbines, especially offshore turbines are shutdown for a prolonged period of time due to failures and degradation of components under severe weather conditions. Repairing offshore wind turbines is costly. Model-based fault detection and controller reconfiguration are two new, partly still experimental techniques, that have the potential to detect faults quickly and minimize the impact of faults in a more efficient way than the currently used classical condition monitoring and control methods can. The combination of fault detection and controller reconfiguration is called fault-tolerant control. Fault tolerant control increases system availability.

A case study was performed to investigate the feasibility of model-based fault detection and controller reconfiguration of wind turbines. The case study was focused on failures of the sensors and actuators in the primary pitch-to-vane control loop and to changes in the gain of this control loop that can be viewed as being due to the occurrence of faults or degradation of components. Two major bottlenecks in the use of fault detection methods for wind turbines are: 1) The operation of a wind turbine in a closed-loop control configuration, which leads to correlation between the input and output signals of the wind turbine; 2) The fact that the closed-loop wind turbine system is driven by an unknown input signal, the rotor effective wind speed. In practice, the wind speed cannot be measured accurately, and therefore it is assumed to be unknown.

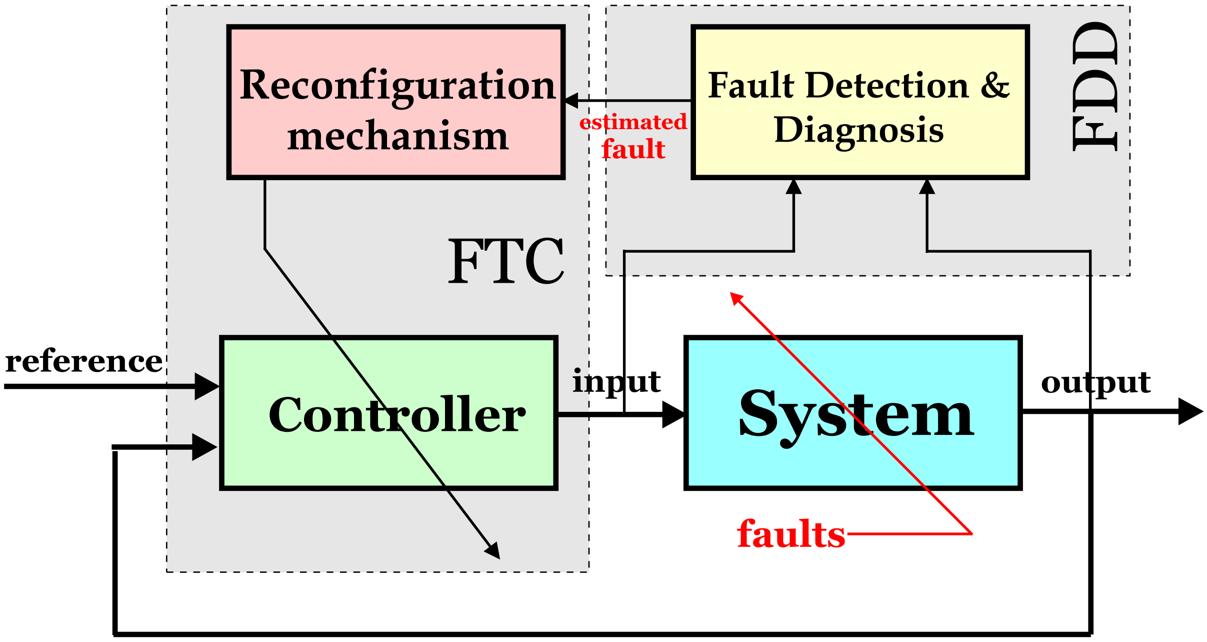

Figure 7: Fault-tolerant control system

The combination of the closed-loop operation and the unknown driving input leads to a complicated setting for performing fault detection. Most currently available fault detection methods are not suited for this scenario. Within this feasibility study dedicated fault detection methods have been developed that can deal with the closed-loop setting and the unknown wind input. These methods are based on a Kalman filter and use a model of the deterministic dynamic behavior of the wind turbine and models of the faults that are to be expected (for example multiplicative actuator faults). The developed methods not only estimate the faults, but also the unknown input signal.

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

Project members: R. Hallouzi, S. Kanev, V. Verdult, R. Babuška, J. Hellendoorn, M. Verhaegen

Sponsored by: STW

The aim is the development of fast and reliable algorithms for fault detection and diagnosis (FDD) and controller reconfiguration (CR). In control systems, faults are events that could cause unwanted behavior or a catastrophe of the controlled system. The design of FTC systems has therefore the purpose to prevent the degradation from simple faults into serious system failures, since system failures might lead to huge economical and human losses. A fault-tolerant system consists of two main parts (see Figure 7): one that has the task to detect and diagnose faults that occur in the control system, and another that reconfigures the controller accordingly, whenever faults occur in the system, so that the performance of the reconfigured faulty closed-loop system is preserved at some desired level.

The goal in the project is the development of numerically fast and robust algorithms

for on-line implementation, applicable to the problems of FDD and CR in cases of both abrupt and incipient system faults in the sensors, actuators and physical parameters in the system. The project is subdivided into two work packages, one dealing with fault detection and isolation (researcher R. Hallouzi, started in 2004), and another focused on the problem of controller reconfiguration (researcher S. Kanev, 1999-2003).
Within **Work Package I** the main focus is put on the following items:

- the augmented Kalman filter for the estimation of multiplicative and additive sensor and actuator faults,
- LPV based FDI for dealing with non-linear systems.
- FDI methods that provide information on the uncertainty of the identified faults.
- evaluation of FDI methods on a non-linear aircraft model that may include component faults.

Within **Work Package II** different approaches have been developed:

- FTC based on multiple-model estimation and predictive control,
- reconfiguration strategies for robust LQ regulator/Kalman filter,
- a BMI approach to passive FTC,
- an ellipsoid algorithm for probabilistic robust controller design,
- active LPV-based FTC in the presence of uncertainty in the FDI,
- a randomized approach to robust output-feedback MPC.

4.16 Fuzzy control of multivariable processes

Project members: R. Babuška, S. Mollov

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. Extensive research has been devoted to single-input single-output fuzzy control systems, including modeling and control design aspects, analysis of stability and robustness, adaptive control. Multivariable fuzzy control, however, have received considerably less attention, despite strong practical needs for multivariable control solutions, indicated among other fields 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. Recent developments include effective optimization techniques and robust stability constraints for nonlinear model predictive control. The developed predictive control methods have been applied to the design of an Engine Management System for the gasoline direct injection engine benchmark, developed as a case study within the European research project FAMIMO (see Figure 8). An extension of the Relative Gain Array approach has been proposed that facilitates the analysis of interactions in MIMO TS fuzzy models. The results of this research are reported in the Ph.D. dissertation by S. Mollov.

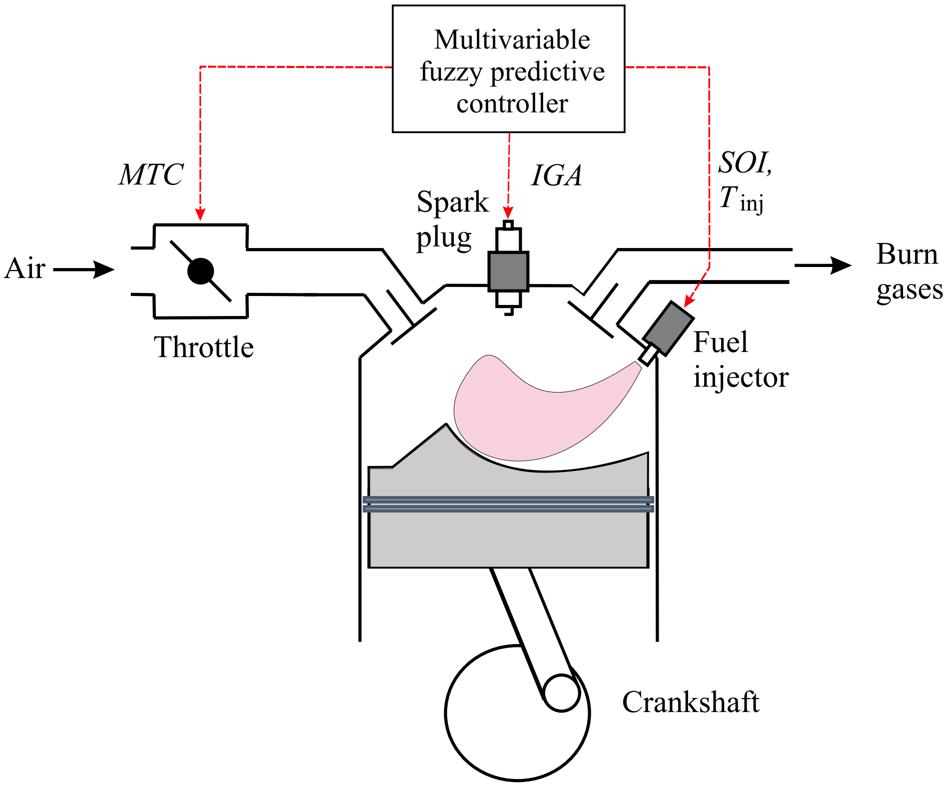

Figure 8: Fuzzy predictive control of a gasoline direct injection engine.

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

Project members: M. Oosterom, R. Babuška, V. Verdult

Sponsored by: European Community GROWTH project ADFCS–II

The objective of this project is to apply the fly-by-wire (FBW) technology in flight control systems of a smaller category of aircraft (see Figure 9). In FBW digital flight control systems, there is no direct link between the control stick and pedals, which are operated by the pilot, and the control surfaces. All measured signals, including the pilot inputs, are processed by the flight control computer that computes the desired control surface deflections. This scheme enables the flight control engineer to alter the dynamic characteristics of the bare aircraft through an appropriate design of the flight control laws. Moreover, important safety features can be included in the control system, such as flight envelope protection. This increases the safety level compared to aircraft with mechanical control systems.

Our task in the project is to assess the benefits and to verify the validity of the soft-computing techniques in the FBW control system design and sensor management. These novel techniques are combined with standard, well-proven methods of the aircraft industry. The research topics are the design of gain-scheduled control laws, fault detection, isolation and reconfiguration, and an expert system monitoring of the overall operational status of both the pilot and the aircraft. For the FCL optimization and the fault detection and identification system, fuzzy logic approaches are adopted in order to extend linear design techniques to non-

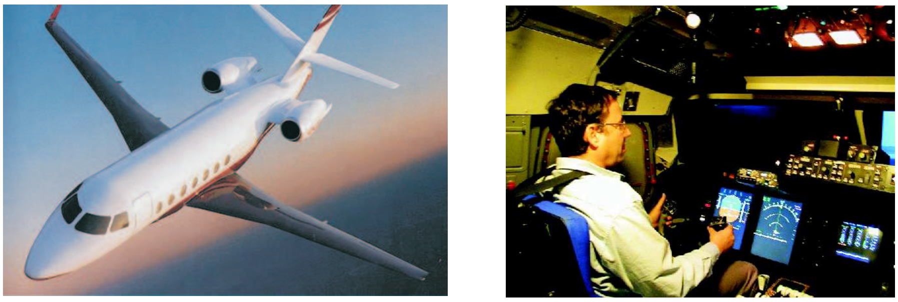

Figure 9: Galaxy business jet (left) and validation of the control system through pilot-in-the-loop simulations at the Research Flight Simulator of the NLR (right).

linear systems. Moreover, a neuro-fuzzy virtual sensor is being developed in close cooperation with Alenia to replace hardware sensors. For the pilot-aircraft status monitor a fuzzy expert system will be developed that has the functionality of a warning and advisory/decision aiding system.

4.18 FDI applied to affordable digital fly-by-wire flight control systems

Project members: R. Hallouzi, R. Babuška, V. Verdult, M. Verhaegen

Sponsored by: European Community GROWTH project ADFCS–II

Employing analytical redundancy based on mathematical models rather than hardware redundancy based on redundant hardware is a key issue in current research in the area of aircraft fault detection and identification (FDI). In this manner cost, weight and complexity can be reduced. The objective of this project is to apply model-based FDI methods to small commercial aircraft (see Figure 10). In previous work within the ADFCS-II project research has mainly focused on sensor faults. However, in order to achieve complete condition monitoring in aircraft, the development of FDI methods for actuators is an important step.

The FDI methods we propose are able to distinguish between total and partial actuator faults in an aircraft and can estimate how large these faults are. Partial faults are characterized by the fact that the control surface is still functioning, but only with reduced power (loss-of-effectiveness). Total faults are characterized by the fact the control surface is stuck at a certain position and does not react on the control input (e.g. stuck-in-place or hard-over fault).

The use of well-proven linear FDI methods is attractive in many aspects. However, aircraft are non-linear systems. In order to still be able to apply these linear FDI methods, multiple linear models have to be scheduled. These models are linearized at certain points in the flight envelope of the aircraft. The challenge is to use as few linearized models as possible to cover the whole flight envelope.

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

Project members: R. Babuška, J. Abonyi (University of Veszprem, Hungary)

Effective development of nonlinear dynamic process models is of great importance in the application of model-based control. Typically, one needs to blend information from different

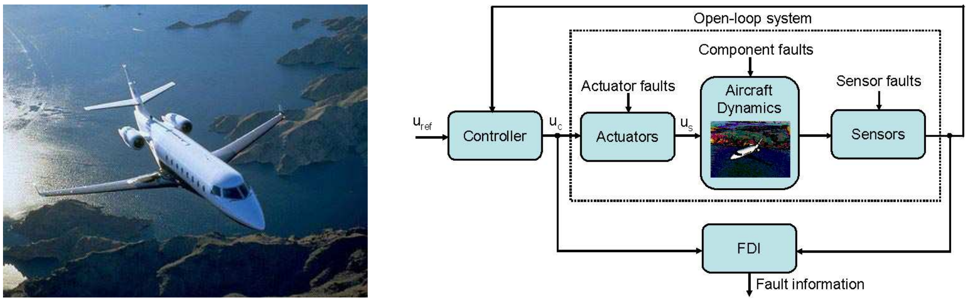

Figure 10: Galaxy business jet (left) and a schematic overview of a control system with model-based FDI (right).

sources: experience of operators and designers, process data and first principle knowledge formulated by mathematical equations. 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 on the model parameters are based on the knowledge about the process stability, minimal or maximal gain, and the settling time. The algorithm has been successfully applied to off-line and 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, 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. 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 modeling and model-based control of nonlinear systems.

4.20 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, e.g., 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 analysis (linearizing) 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 the interconnection and energy properties of the system. For that, a general energy-based modeling procedure for

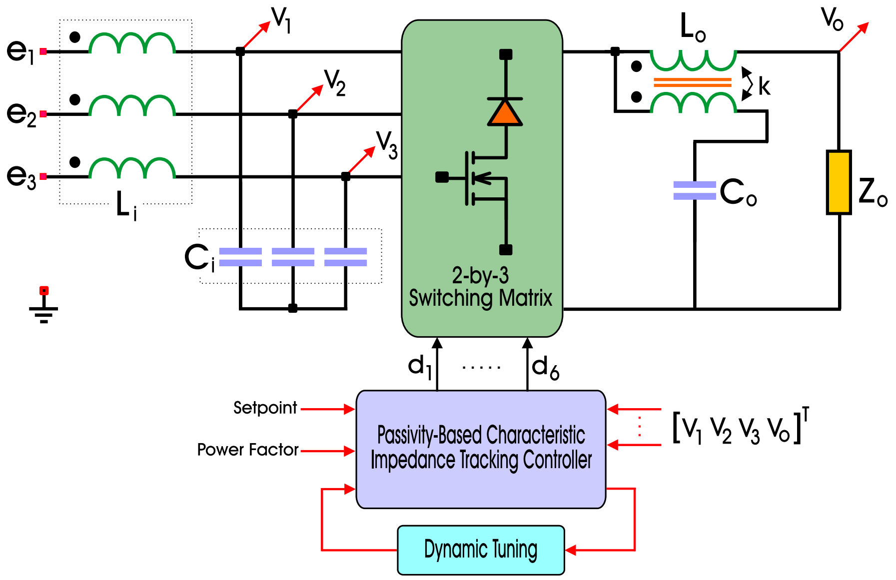

Figure 11: Passivity-based controlled AC-to-DC Buck type converter.

(single and multiple) switched-mode electrical networks has been developed. The method is a synergy of the well-known Hamiltonian and Lagrangian formalism together with the Brayton-Moser equations. This technique is useful for, e.g., passivity-based control purposes and large signal stability analysis. As case studies, fundamental single switch DC-to-DC converters and multi-switch AC-to-DC rectifiers were used (see Figure 11). Further research includes the involvement of several classes of non-ideal physical elements into the framework.

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.

4.21 Stabilization of nonlinear RLC circuits: power shaping and passivation

Project members: D. Jeltsema, J.M.A. Scherpen, Romeo Ortega (Supelec, France)

Sponsored by: Marie Curie Control Training Site (CTS)

Passivity is a fundamental property of dynamical systems that constitutes a cornerstone for many major developments in systems and control theory, including optimal ($\mathcal{H}_2$ and $\mathcal{H}_\infty$) control, realization theory and adaptive control. Passivity has also been instrumental to reformulate, in an elegant and unifying manner, the central problem of feedback stabilization

— either in its form of feedback passivation for general nonlinear systems or as energy-shaping control for systems with physical structures.

It is well-known that arbitrary interconnections of passive (possibly nonlinear) resistors, inductors and capacitors define passive systems with supply rate the product of the external sources voltages and currents, and storage function the total stored energy. Interestingly, for a class of RLC circuits with convex energy function and weak electromagnetic coupling it is possible to 'add a differentiation' to the port terminals preserving passivity — with a new storage function that is directly related to the circuit power. The result is of interest in circuits theory, but also has applications in control problems as it suggests the paradigm of Power Shaping stabilization as an alternative to the well-known method of Energy Shaping as recently proposed in the literature. In contrast with Energy Shaping designs, Power Shaping is not restricted to systems without pervasive dissipation and naturally allows to add 'derivative' actions in the control. These important features, that stymie the applicability of Energy Shaping control, make Power Shaping very practically appealing. To establish our results we exploit the geometric property that voltages and currents in RLC circuits live in orthogonal spaces, i.e., Tellegen's theorem, and heavily rely on the seminal paper of Brayton and Moser in 1964.

Additional research includes the extension of our results beyond the realm of RLC circuits, e.g., to mechanical or electromechanical systems. A related question is whether we can find Brayton-Moser like models for this class of systems.

4.22 Real-time control of smart structures

Project members: M. Verhaegen, P.R. Fraanje, N. Doelman (TNO)

Smart materials is a notion used for materials that deform when electrically actuated and vice versa produce an electrical signal when they are deformed. What makes these materials "smart" is the signal and control processing schemes that actively controls the interaction between the material and structure to which the materials are attached.

These structures can at a large scale be flexible. In that case the smart controller design artificially adapts the stiffness of the structure, or changes its shape in order to optimize the plant performances. Examples are the active shaping of the using profile to maximize the drag in different flight phases. At a nano-scale, smart materials are used for high-precision positioning in, e.g., Atomic Force Microscopes. The research challenges addressed in the project are both fundamental:

- Modeling and control of the nonlinear phenomenon such as hysteresis and creep of piëzo-electric material;
- Decentralized control of large scale systems with distributed sensors and actuators;

as well as practically oriented:

- Real-time implementation of Matlab simulink phototyped control schemes making use of real-time Linux.

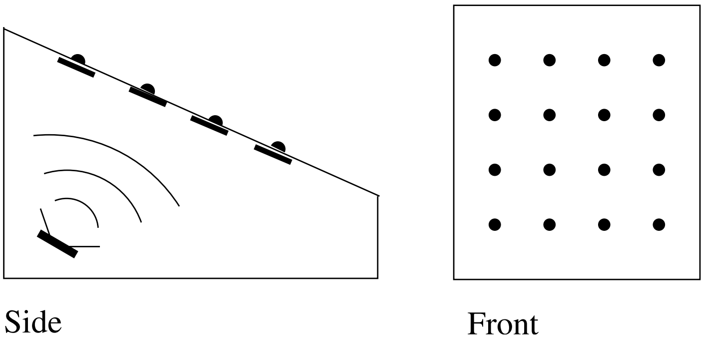

Figure 12: Schematic representation of the vibrating plate experimental set-up with collocated piëzo-sensors and actuators; the loudspeaker is the disturbance source.

5 Industrial process control

The relevant trends in process industry could be summarized as: better profitability, increased flexibility and the incorporation of sustainability. The current research focus is on profitability and flexibility and could be summarized as model-based control/optimization of "difficult" unit operations and complete plants. In this research three aspects can be recognized:

1. **Modeling**: this includes modeling, validation, identification and reduction. After modeling we should end up with a model that has sufficient accurate predictive power at acceptable computational cost.
2. **Observation**: Attention is paid to extended Kalman filters and horizon estimators.
3. **Control/optimization**: The research in this area concentrates on dynamic optimization (sequential and simultaneous approach) but also on the integration of control and optimization.

This research is done in close cooperation with the process industry: Bayer, Shell, Solvay, AKZO, Unilever, …

5.1 Economic optimal plantwide control

Project members: A.E.M. Huesman

The objective of plantwide control (the control of a complete chemical plant) can be formulated as:

1. support (not guarantee) safety,
2. realize the required conversion,
3. minimize the operating costs.

It should be noted that the three aspects of the objective are mentioned in the *order of economic importance.* The support of safety is essential to avoid (economic) loss, the required conversion is a necessary condition to make profit and minimizing the operating costs leads to maximum profit.

There are at least two approaches to realize this objective. The first approach is *traditional.* This approach focuses on the required conversion and tries to realize this by *control.* If necessary or possible the support of safety and the minimization of the operating costs is also handled by control. An advantage of this approach is that it leads to control problems that can be solved easily *real-time.* A disadvantage is that it does not minimize the operating cost to the lowest possible level, so potential profit is lost. Another disadvantage is that the traditional approach only works well for *continuous* processes.

The second approach uses the objective to formulate a dynamic *optimization* problem:

$$\begin{aligned} \min_{\text{DOF over time}} & (\text{operating costs}) \\ \text{s.t. } & \text{support of safety,} \\ & \text{required conversion} \\ & \text{and plant behavior} \end{aligned}$$

DOF stands for Degrees Of Freedom (valve positions etc.), s.t. for subjected to. The optimization approach is attractive since it leads to *economic optimal* plantwide control. Furthermore it can not only handle continuous processes but also *batch* processes. However the typical size of the optimization problems involved is considerable (the number of variables and equations is $\approx 10^3 - 10^5$). And the effect of disturbances can only be taken into account by repeating the optimization *real-time*. The current research concentrates on the question how to solve large optimization problems real-time (in a plantwide control context).

5.2 Closed-loop model predictive control

Project members: D.H. van Hessem, O.H. Bosgra

Sponsored by: GROWTH Program of the European Union

During the last twenty years, process control and optimization has focused on open-loop predictive methods. The main disadvantage of these open-loop methods is that feedback is only generated by means of a receding horizon strategy. Consequently, model predictive control suffers from the limitation of any open-loop strategy, namely that the possibility of shaping the process sensitivity, a basic characteristic of feedback design methods, is completely absent. As a consequence, robustness is and always has been a problem with MPC. To overcome these inconsistencies a closed-loop formulation has been developed making an explicit use of both feedforward and feedback in a generalized plant setup. An example of such a control solution is visualized in Figure 13.

5.3 Model reduction for dynamic optimization of chemical processes

Project members: J. van den Berg, O.H. Bosgra

Sponsored by: GROWTH Program of the European Union

Process industry has become more market driven. Nowadays, e.g. in the polymer industry customers require between 30–100 varieties of product grades due to wide variety of costumer products. The grades have to be produced within tight specifications and against competitive price using an increasing variation in input quality of feedstock material. Difficulties of production units to adapt to this demand lead to unnecessary resource usage waste production, energy usage and higher cost.

Current control and optimization systems do not support the dynamic non-linear process behavior of production plants. They cannot use dynamic process models (too complex) and no adequate algorithms exist. INCOOP is aiming at fully integrated dynamic and non-linear process control and optimization.

The contribution of this research is the assessment of existing and development of new model reduction techniques that exploit the available first principle models and reduce the computational load for the optimization.

5.4 Rigorous model-based control strategy for batch crystallizers (CrysCODE)

Project members: A.N. Kalbasenka, A.E.M. Huesman, O.H. Bosgra

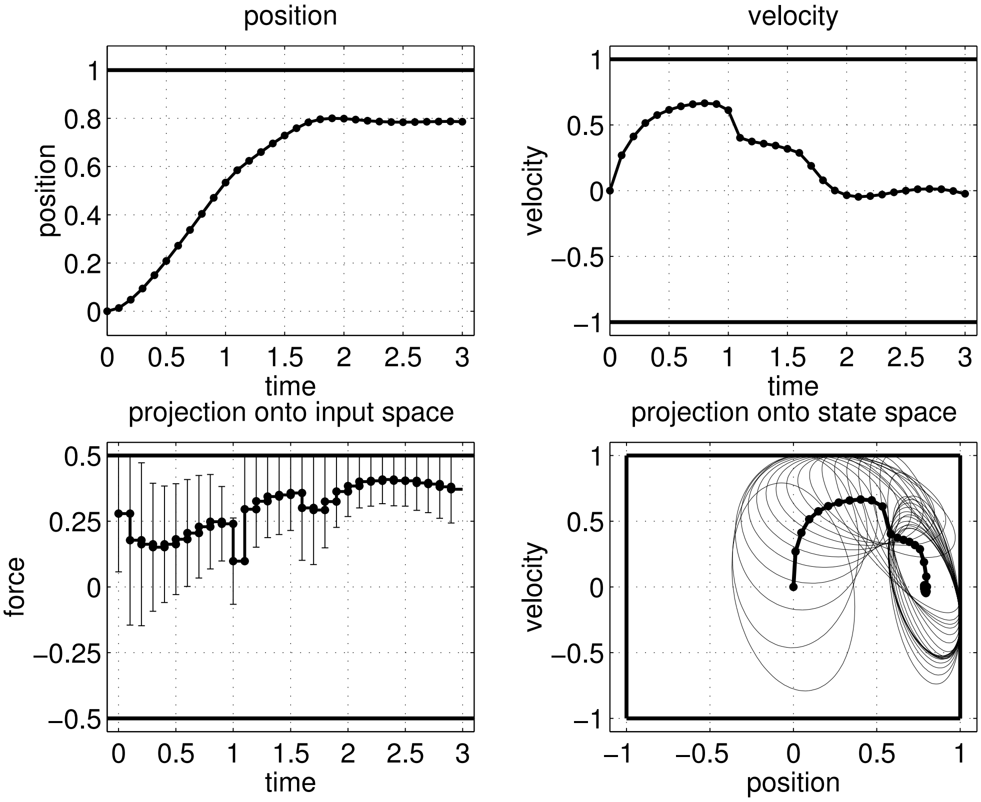

Figure 13: Visualization of a closed-loop predictive control solution.

Sponsored by: AKZO-Nobel, BP-Amoco, DSM, Purac BioChem, Solvay

This research is a part of the multi-disciplinary research project CrysCODE (Crystallizer COntrol and DEsign).

The ultimate goal of the present research is to design a model-based control system for batch crystallization processes. This ambiguous research title can be elaborated further resulting in the following subgoals:

- validation of the models for a crystallizer (draft-tube and draft-tube-baffle crystallizers;
- validation of the models for process actuators (conventional and ultrasonic seeding techniques, impeller frequency);
- validation of the model for a measurement system (crystal size distribution measurement and supersaturation measurement devices);
- model reduction;
- design and validation of a dynamic observer (extended Kalman filter);
- design and validation of a model predictive controller.

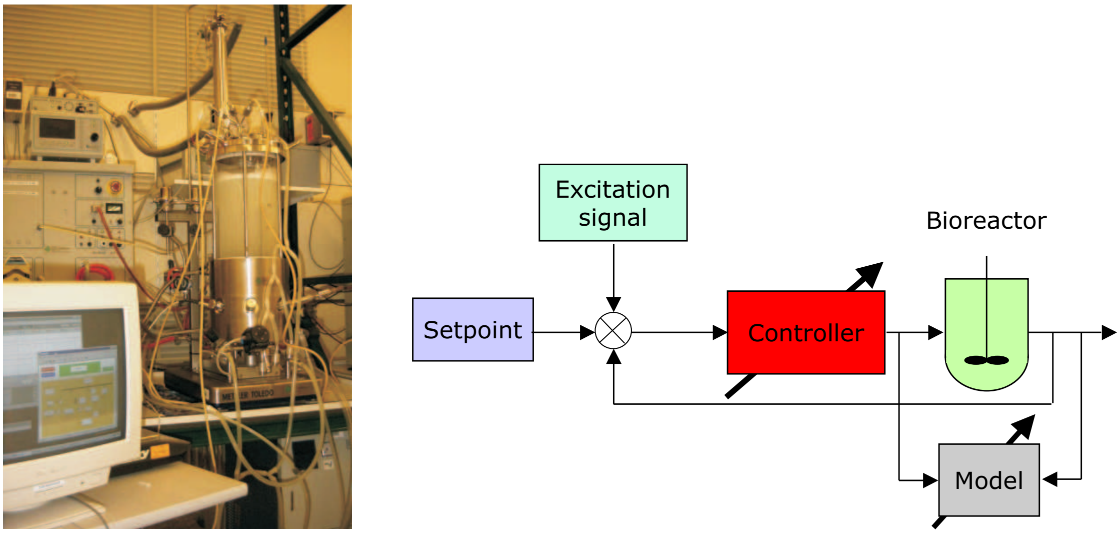

Figure 14: Experimental laboratory setup (left) and the basic model-based adaptive control scheme (right).

5.5 Intelligent adaptive control of bioreactors

Project members: R. Babuška

The goal of this research is the development and implementation of a robust self-tuning controller for fermentation processes. To ensure an optimal operating conditions, the pH value, the temperature and the dissolved oxygen concentration in the fermenter must be controlled within tight bounds. Ideally, the same control unit should be able to ensure the required performance for a whole variety of fermentation processes (different microorganisms), different scales (volume of one liter to several thousand liters) and throughout the entire process run. Figure 14 shows an experimental laboratory setup used in this project. The main control challenge is the fact that the dynamics of the system depend on the particular process type and scale and moreover are strongly time-varying, due to gradual changes in the process operating conditions.

Controllers with fixed parameters cannot fulfill these requirements. Self-tuning and adaptive control is applied to address the time-varying nature of the process. Among the different types of adaptive controllers (model-free, model-based, gain-scheduled, etc.), the model-based approach is pursued. The model is obtained through a carefully designed local identification experiment. Special attentions is paid to the robustness of the entire system in order to ensure safe and stable operation under all circumstances. The main contribution of this research is the development, implementation and experimental validation of a complete self-tuning control system. The robustness of the system is achieved by combining well-proven identification and control design methods with a supervisory fuzzy expert system. This research is being done a cooperation with Applikon Dependable Instruments B.V., Schiedam.

5.6 Artificial intelligence for the control of a hopper dredger

Project members: J. Braaksma, R. Babuška, J.B. Klaassens

Figure 15: The "Rotterdam" dredger during first sea trials. Source: Ballast Ham Dredging 2001.

Sponsored by: IHC Systems, Senter

This project is a cooperation of the Delft Center for Systems and Control with IHC Systems, a company specialized in the development and manufacturing of automation systems for dredgers. Although modern trailing suction dredgers are equipped with advanced dynamic positioning and tracking systems, there is need for an on-board decision-support system that will advise the operators on a control strategy leading to optimal dredger performance under given operating conditions.

The dredging process can be subdivided into two main subprocesses: trailing (propulsion of the ship) and dredging (excavation of the soil from the sea bed and its transport to the ship). Set-points for manipulated variables influencing these processes are determined by two human operators. Consequently, the performance and efficiency of the entire dredging process heavily depend on the experience and insight of these operators.

Changes of external variables that have large influence on dredging efficiency, such as the type of soil, dredging depth, water current, etc., require that the operators must constantly change the important settings of the manipulated variables. These include the propeller pitch, the pump drives, the visor angle, swell compensators, etc., when these actuators are controlled manually, or the corresponding set-points for trail speed, mixture speed, soil-water mixture density, etc., when controlled automatically.

An important constraint is the limited amount of energy available on-board. Proper distribution of the energy among the different subprocesses is thus crucial. In addition, different operating strategies can be used in different dredging projects, such as the maximization of the production rate vs. optimization of efficiency and awareness of maintenance and fuel costs.

The goal of this project is to develop an adaptive decision-support system that will advises the operators on the most suitable control strategy, given a specified goal, such as the minimization of the integral dredging costs per m^3 or the maximization of the production per time

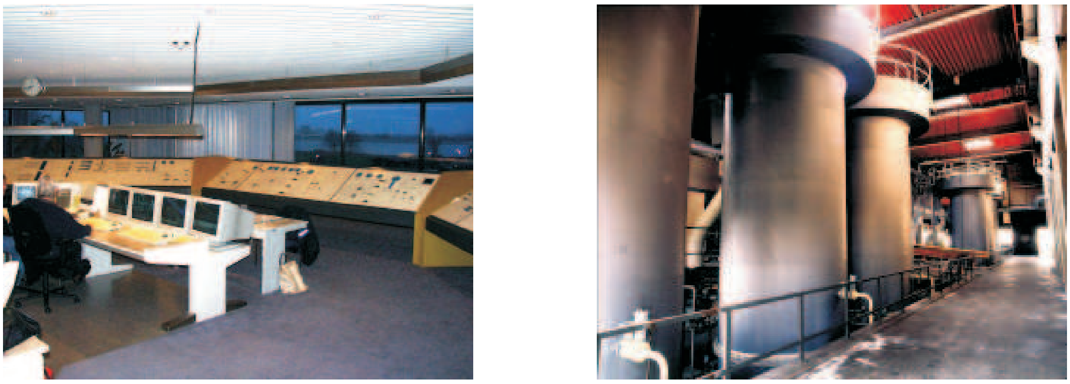

Figure 16: The control center of the Amsterdam Water Supply plant (left) and the softening reactors (right).

unit. The system will make use of available knowledge in the form of (partial) mathematical models of the process and will also involve on-line learning and adaptation during operation.

5.7 Grey-box modeling and plant-wide integrated control of water purification processes

Project members: K.M. van Schagen, R. Babuška, J.M.A. Scherpen

Sponsored by: Senter

This project, called Promicit (Process Modeling and Integrated Control of Water Treatment), is a cooperation between Amsterdam Water Supply, ABB, DHV and the Delft University of Technology – Department of Civil Engineering and Delft Center for Systems and Control.

Currently, water treatment plants are primarily controlled by experienced operators, based on laboratory and on-line measurement of water quality parameters. The goal and the challenge of this project is to develop models of the complete water purification plant, by using first principles (chemical, biological and physical) as well as novel gray-box, data-driven techniques. Based on these models, an automatic control system will be designed for integrated, plant-wide control of the entire process chain. This system can be used both for on-line process control and for decision support. The main treatment steps considered in this project are ozonation, softening and biological active carbon filtration. It is expected that by using advanced modeling and control techniques, water supply companies will gain more insight in the operation principles of the plant, improve monitoring, prediction and control of the processes and thus will consistently produce high-quality drinking water.

In a first pilot study, a model-based predictive controller for the softening process stage (consisting of several pellet reactor operating in parallel, see Figure 16) was developed. This process was selected as it is relatively independent of the other treatment steps, the chemical and physical principles are well understood and a sufficient number of sensors and actuators are available. The softening controller should maintain the desired water hardness and at the same time minimize the super-saturation of calcium in order to prevent calcium deposits in later water treatment steps.

First, a model was developed within the Stimela environment under Matlab and Simulink. Sensitivity analysis has been conducted on this model to identify the most important param-

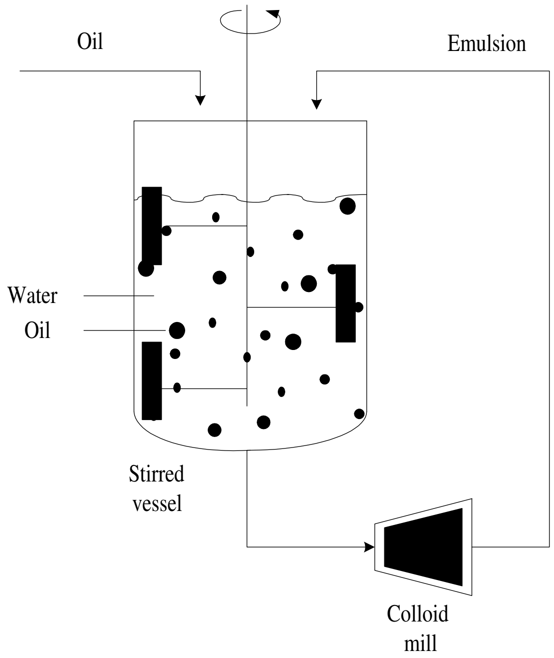

Figure 17: Equipment for the production of o/w-emulsions.

eters and to compute the uncertainty bounds in the predicted outputs. The parameters of the model were optimized by using process data. A hierarchical control structure was proposed to comply with the requirement of constant effluent hardness and minimal super-saturation. A supervisory control level is responsible for determining optimal water flow and reactor effluent hardness set-points. Local controllers take care of the actual control of the individual softening reactors. The performance of the local controller was evaluated in four different scenarios and it was compared with the controller currently used in the plant.

5.8 Model based optimization of emulsification processes

Project members: M. Stork, J. Wieringa, O.H. Bosgra

Sponsored by: EET

Emulsification is a key manufacturing technology in the food industry. Examples of emulsions are mayonnaise and many kinds of dressings. For the manufacturing of these products oil and water (or more general an oily and an aqueous phase), surfactants, ingredients and energy are needed. Equipment as used for the production of oil-in-water (o/w) emulsions is shown in Figure 17. It consists of a stirred vessel in combination with a colloid mill and a recirculation loop. The colloid mill consists of a stator and a rotor. In the narrow gap between these the intensity of the hydrodynamic forces acting on the drops is very high, which causes the breakage of the oil drops. The colloid mill also acts like a pump resulting in a recirculating flow to the vessel. The process is operated fed-batch wise and typical production times are in the order of 10-20 minutes.

In industrial practice the operation procedure is conventional in the sense that the oil flow addition rate and the stirrer and rotor speed (the input variables) have constant val-

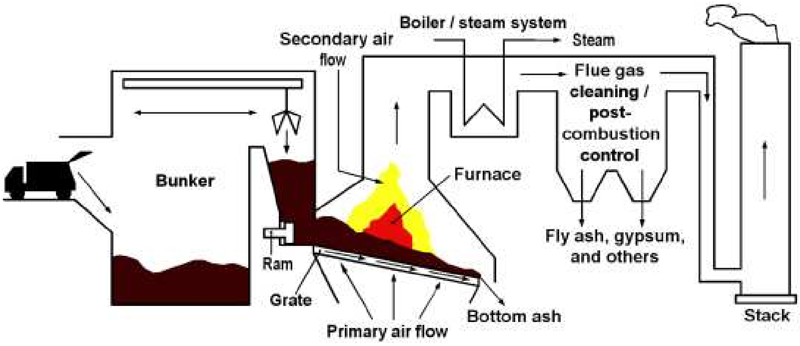

Figure 18: Schematic view of a typical MSW combustion plant.

ues in time. After the oil addition the process is continued for a certain time to ensure a sufficient drop size reduction. For profit maximization it is desirable to decrease the production time while maintaining the product quality specifications. Experiments are expensive and time-consuming; therefore a model-based optimization approach is followed here. The emulsion quality is strongly affected by the drop size distribution (DSD). The desired DSD is often multi-modal and/or asymmetric. This makes the control of the moments of the DSD inadequate and creates the need for the control of the full distribution. The objective of the research is to chose the control inputs such that a certain predefined terminal DSD is reached in minimal time. The research comprises (physical) modeling, parameter estimation, model validation and optimization of the operation procedure.

5.9 Model predictive control of municipal solid waste plants

Project members: M. Leskens, L.B.M. van Kessel, P.M.J. Van den Hof, O.H. Bosgra

Sponsored by: TNO-MEP

The incineration of municipal solid waste (MSW), i.e., household waste, is used for the reduction of the amount of waste and for the production of energy. It is typically performed at a plant of the form that is depicted in Figure 18. Such an MSW combustion plant is subject to both economic and environmental operational and, thereby, control objectives. Economic objectives are, e.g., maximization of the waste throughput, maximization of the energy output and maximization of the lifetime of the components of the MSW combustion plant. Environmental objectives are, e.g., upper bounds imposed on potentially contaminating components of the flue gas. Part of these objectives are supporting each other, e.g., maximization of the waste throughput implies maximization of the energy output, and part of the objectives are conflicting, e.g., the objective of maximization of the waste throughput and energy output conflicts with the demand of maximizing the life time of the components of the MSW combustion plant.

Among many MSW combustion plant managers there is a need to improve their process operation performance. This is due to the ever more stringent environmental regulations and ever growing higher energy demands. An essential tool for the fulfillment of the increasingly higher and tighter economic and environmental objectives is (apart from operators) a combustion control system. Such a combustion control system is typically a network of proportional

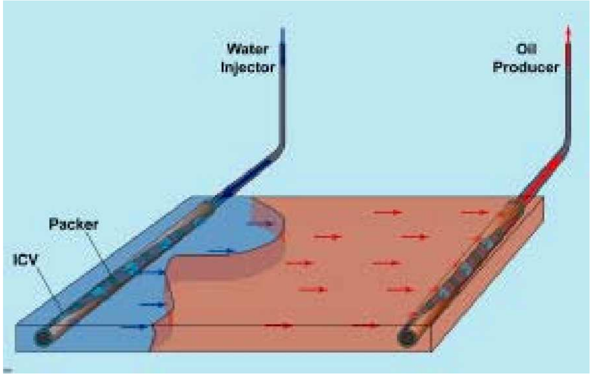

Figure 19: A smart field in which oil is produced through waterflooding.

and, sometimes, integrating (PI) controllers, which at best fulfills the mentioned objectives in a suboptimal manner. An alternative which is thought to be able to deliver a much better control performance is model predictive control (MPC). The reason(s) for this expectation is that MPC is thought to be able to deal much better with the following typical characteristics of the MSW combustion control problem: (i) multiple, conflicting objectives, (ii) the multivariable interacting nature of the process, and (iii) constraints.

The aim of this research project is to investigate the feasibility of MPC as a tool for improving the process operation performance of MSW combustion plants. Aspects of the research are, amongst others, (i) modeling of MSW combustion plants via linear system identification techniques and (ii) nonlinear MPC using a first-principles model that describes the main dynamical phenomena taking place during the MSW combustion process and which is of low complexity (i.e., with respect to the number of (differential) equations of the model). If all works out well, (N)MPC will be tested on a real-life large-scale MSW combustion plant.

5.10 Model-based optimal process operational strategies in reservoir engineering using quantified model-uncertainty estimates

Project members: M.J. Zandvliet, P.M.J. Van den Hof, O.H. Bosgra

Sponsored by: Shell

Smart field technology is an emerging development in the oil and gas production industry (see Figure 19). It involves the application of measurement and control concepts to optimize the production of hydrocarbons over the lifecycle of a reservoir, and includes aspects such as measurement, data transmission, data handling and data interpretation, system modeling, uncertainty quantification, decision-making under uncertainty, optimization and control (cf. Figure 20). Smart fields technology may allow us to go from passive/reactive production scenarios to active/proactive production control.

This project concerns the development of control and optimization techniques for the optimal operation of reservoirs on the basis of dynamic models containing quantified uncertainty.

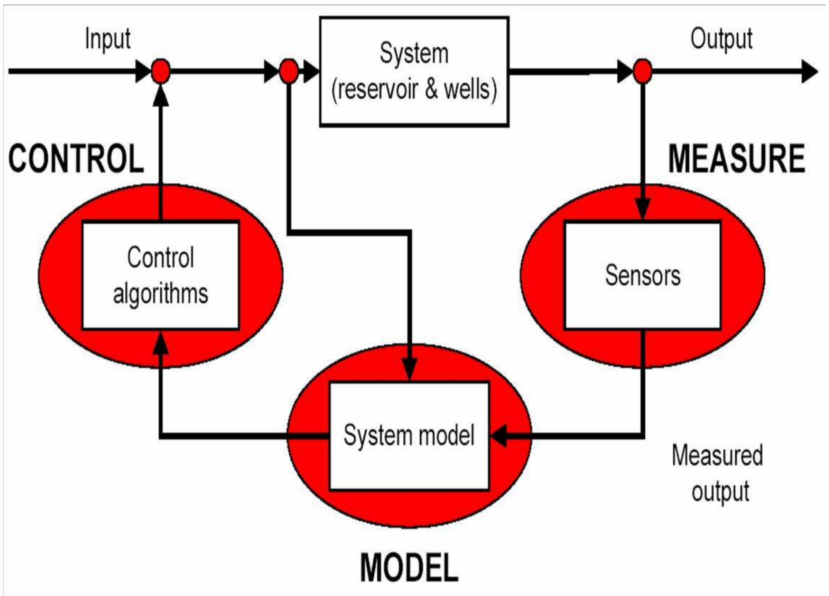

Figure 20: Oil production represented as a model-based closed-loop control process.

6 Mechatronics and micro-systems

Control engineering methods are developed for mechatronic systems of the scale of millimeters and micrometers. Examples of applications are in adaptive optics where use is made of a deformable mirror with a large array of sensors and actuations, position control in a micro compact disk or hard disk, etc. Also on the macro-scale the DCSC collaborates with industrial partners like Océ, IHC-Systems, SKF, TNO, etc. to develop control strategies for innovative mechatronic designs, such as X-by-wire steering or braking.

6.1 Fixed order controller synthesis for electro-mechanical servo-systems

Project members: C.W.J. Hol, C.W. Scherer

Sponsored by: Philips CFT

The demanding requirements on speed and accuracy on electro-mechanical servo-systems imply the use of multi-variable feedback control based on a dynamic model of the system. A state-of-the-art method for multi-variable controller synthesis is through H_∞ optimization.

One of the main disadvantages of H_∞ controller synthesis is the high order (McMillan degree) of the resulting controller which equals the order of the dynamical model plus the order of the weighting functions, typically in the range of about one hundred. In real-time implementations on electro-mechanical systems with a very high sampling rate (typically around 1 kHz), the computation of the controller action becomes more expensive with increasing controller order. This reveals the need for a low-order controller synthesis method which goes beyond existing techniques in being applicable to systems of order larger than fifty.

This research project aims at developing a synthesis method to compute fixed-order controllers for higher-order models of electro-mechanical servo-systems. The algorithm must be implemented in a numerically stable fashion to facilitate the dissemination of reduced order H_∞ synthesis in the industrial practice.

6.2 Vibration isolation and suppression applied to mechanical servo-systems

Project members: M.I. Parra Calvache, P. Valk, O.H. Bosgra

Sponsored by: International Research Institute for Simulation, Motion and Navigation

The SIMONA Research simulator is a lightweight re-configurable cockpit mounted over a 6-DOF motion platform. It is desired that this simulator work with a wide bandwidth, from 10 Hz to 15 Hz, that would allow the simulation of special conditions. The requirements of higher speed and acceleration, and the desired high performance forced the use of lighter structures that have as drawback higher flexibility and more susceptibility to unwanted vibrations. Within this framework, it is our main interest to compensate for bending and vibrations over the components of the video display system, namely the projectors, the back projection screen and the mirror and to allow the high performance use of the motion hydraulic system for the simulation of special conditions. As a first approach, it is important to analyze the interaction between Video Display System components and how their performance is affected by the reference motion necessary to give the pilot the impression of real flight. This clearly involves knowledge over the flexible-multi-body cockpit structure and video display system. For this end, we will use experimental modelling tools giving emphasis to identification of

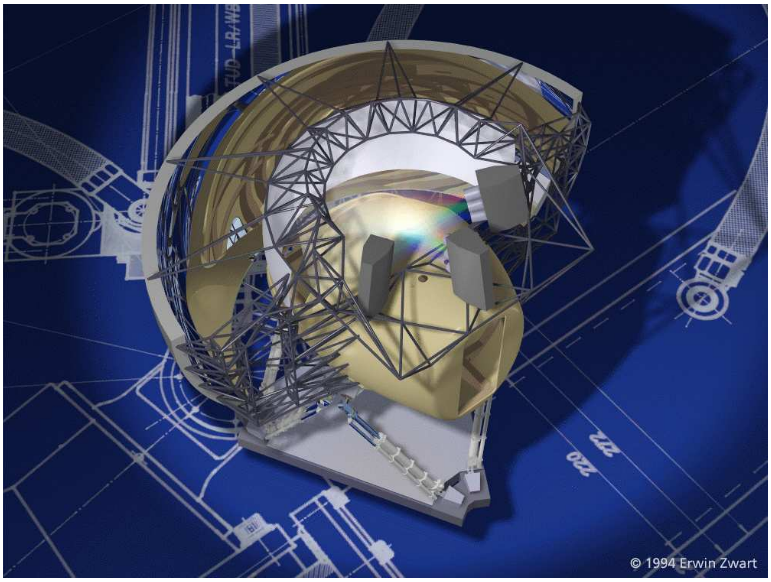

Figure 21: Diagram of the SIMONA Research Simulator visual display system

multivariable systems in closed-loop and modal identification for mode shape representation. Further, we want to suppress unwanted vibration that deteriorates not only the performance but eventually the structural integrity of mirror or screen. As a first approach input shaping algorithms will be studied as passive damping technique keeping open possibilities of extra feedback (signals related to the performance of the Video Display System) aiming to a final active control of vibration of the cockpit structure.

6.3 Mechatronic redesign for active control of a micro fluid jet system

Project members: M.B. Groot Wassink, S. Koekebakker (Océ), O.H. Bosgra, D. Rixen, J. van Eijk (Delft University of Technology)

Sponsored by: Océ Technologies B.V.

In this research project, a printhead is investigated as example of a micro fluid jet system (see Figure 22). A basic printhead configuration consists of a certain number of channels each actuated by a piezo-actuator. A pressure wave created through actuation of the piezo-actuator is amplified which results in the emitting of a droplet at the nozzle of a channel. The shape of the channels together with the wave form of the pressure field are therefore crucial to the performance of the printhead. Minor actuated modifications on the wave shape under realtime control might considerably amplify the performance. From these considerations stems the idea of the manipulability of the resonator functionality of the printhead by means of active control.

To make optimal use of abilities of active control, a mechatronic redesign of the printhead is required. For one, proper sensor functionality should be build in. This requires a thorough physical understanding of the printhead that involves a comprehensive model describing the influence of all relevant parameters. At the same time, this knowledge is needed to design sensible controllers for the printhead. Practical applicability is to be shown using a test-rig that is available to perform measurements and validate results.

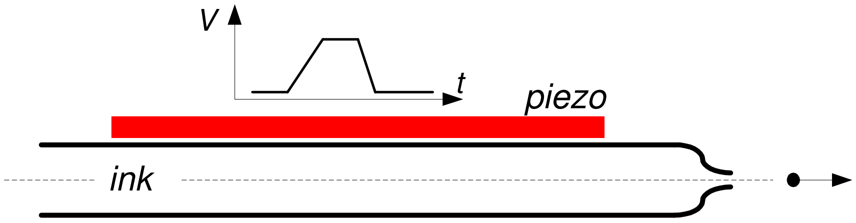

Figure 22: A printhead.

6.4 Control of a jumbo container crane (JCC project)

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

The goal of the project 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 (see Figure 23). The JCC project has the following participants: Siemens Nederland N.V., ECT, Transport Technology group of the Faculty of Mechanical Engineering and Marine Technology of Delft University of Technology), and DCSC.

DCSC contributes with the following research activities:

- development of 2D and 3D mathematical models 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.
- 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.

6.5 X-by-wire

Project members: J.B. Klaassens, E. Holweg (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", see Figure 24). 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

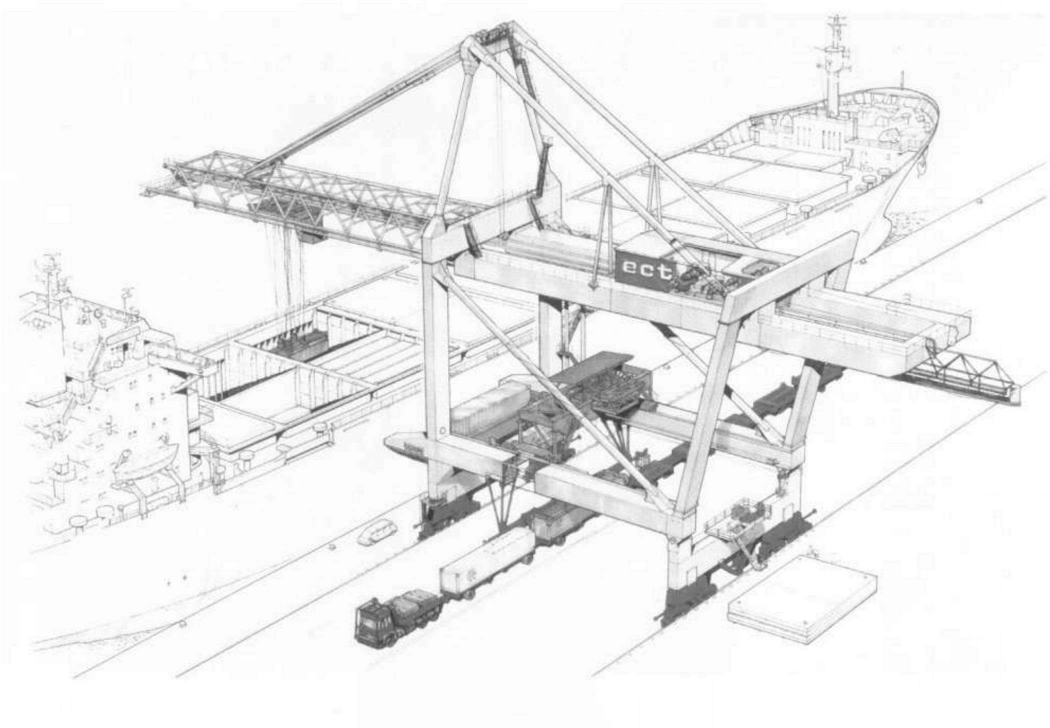

Figure 23: Sketch of the jumbo container crane.

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.

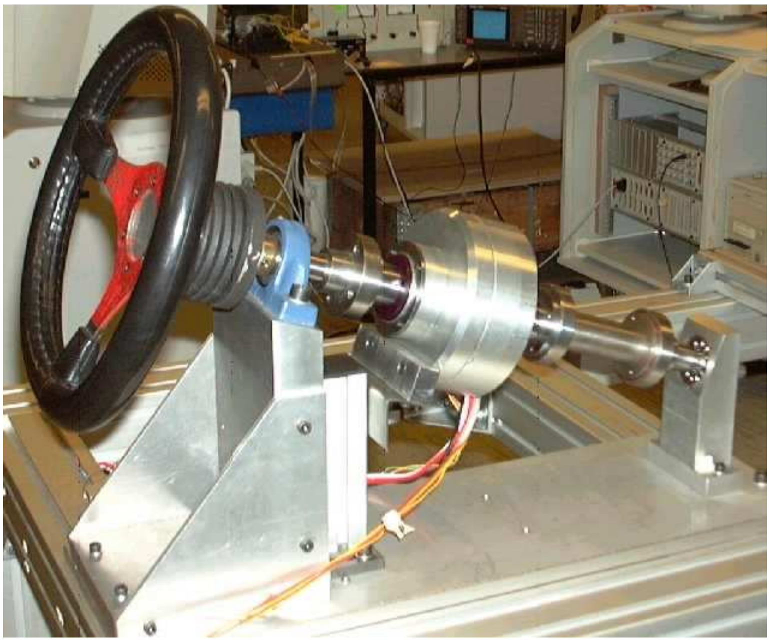

Figure 24: Steer-by-wire.

7 Traffic and transportation control

The traffic and transportation research of DCSC focusses on the control of large-scale transportation system with a main emphasis on freeway and road traffic networks. In addition, we also consider control of railway networks. The primary control strategy is model predictive control. Furthermore, we also consider distributed control of large-scale traffic networks using a distributed and/or hierarchical multi-agent control approach.

7.1 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 model predictive control (MPC) traffic controllers in this project.

In this project we concentrate on two traffic control measures for motorway traffic: ramp metering (see also Project 7.2 and Figure 25) and variable speed limits [25, 24]. More specifically, we apply MPC to optimally coordinate variable speed limits and ramp metering for highway traffic flow control. The basic idea is that speed limits can increase the (density) range in which ramp metering is useful. For the prediction we use a slightly adapted version of the METANET traffic flow model that takes the variable speed limits into account. The optimal control signals aim at minimizing the total time that vehicles spend in the network. The coordinated control results in a network with less congestion, a higher outflow, and a lower total time spent. In addition, the receding horizon approach of model predictive control results in an adaptive, on-line control strategy that can take changes in the system automatically into account.

7.2 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 optimal ramp metering. 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

Figure 25: Ramp metering on the A13 highway in Delft-Zuid.

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 a model predictive control (MPC) approach, which provides a balanced trade-off between computational complexity and global performance. In addition, we have improved an existing simple first-order model to describe the evolution of traffic flows in a motorway network [2]. The results of the computed ramp metering strategy are verified using micro-simulation, in which the movements of each individual vehicle are simulated (see Figure 26).

7.3 Optimal transfer coordination for railway systems

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

In this project we extend the model predictive control framework (MPC), which is a very popular controller design method in the process industry, to railway systems [15, 17, 18]. Usually MPC uses linear (or nonlinear) discrete-time models. However, railway networks and subway networks cannot adequately be described by such models.

First, we have introduced a modeling framework for railway systems with both hard and

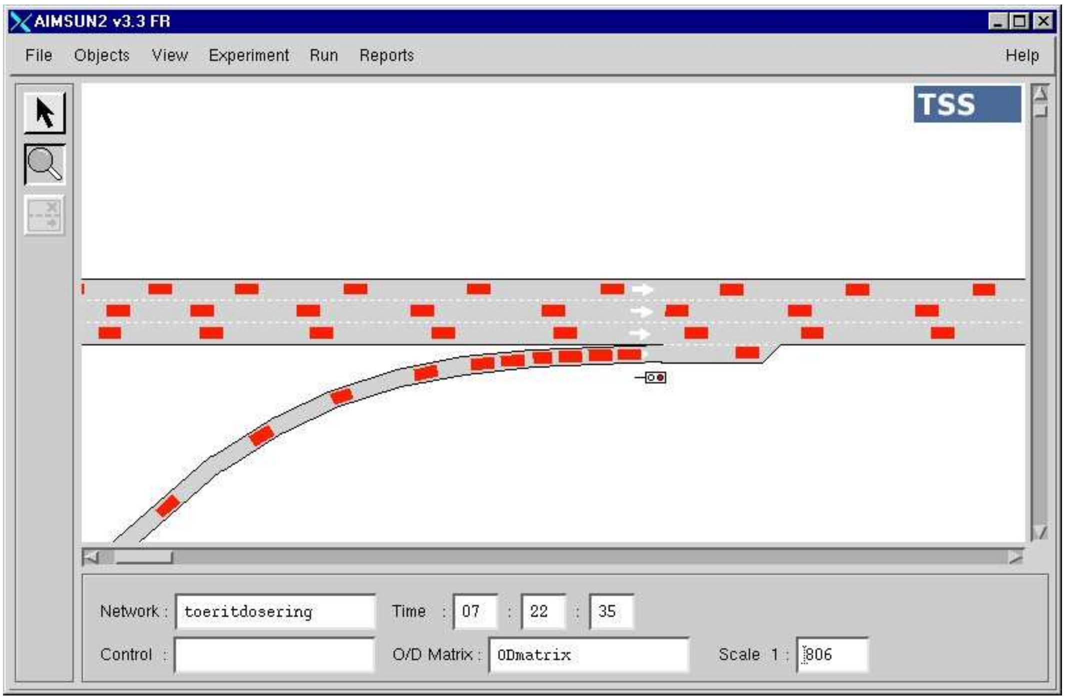

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Figure 26: Screenshot of micro-simulation of ramp metering.

soft connection constraints. A typical example of a *hard* connection constraint in a railway context is when a train should give a guaranteed connection to another train. However, in some cases (e.g., if there are delays) we could allow a train to depart although not all trains to which it should give connections according to the schedule have arrived at the station: if some of these trains have a too large delay, then it is sometimes better — from a global performance viewpoint — to let the train depart anyway in order to prevent an accumulation of delays in the network. Of course, missed connections lead to a penalty due to dissatisfied passengers or due to compensations that have to be paid. Synchronization constraints that may be broken (but at a cost) are called *soft* connection constraints. We also consider an extra degree of freedom for the control to recover from delays by letting trains run faster than their nominal speed if necessary. Of course, this control action will also lead to extra costs (due to increased energy consumption or faster wear of the material).

Next, we have extended the MPC framework to railway systems while still retaining the attractive features of conventional MPC. The main aim of the control is to obtain optimal transfer coordination and/or to recover from delays in an optimal way by breaking connections and/or letting some trains run faster than usual (both at a cost). In general the MPC control design problem for railway systems leads to a nonlinear non-convex optimization problem. We have shown that the optimal MPC strategy can be computed using extended linear complementarity problems or integer programming algorithms.

Other examples of systems with both hard and soft synchronization constraints for which this approach can be used are subway networks and logistic operations.

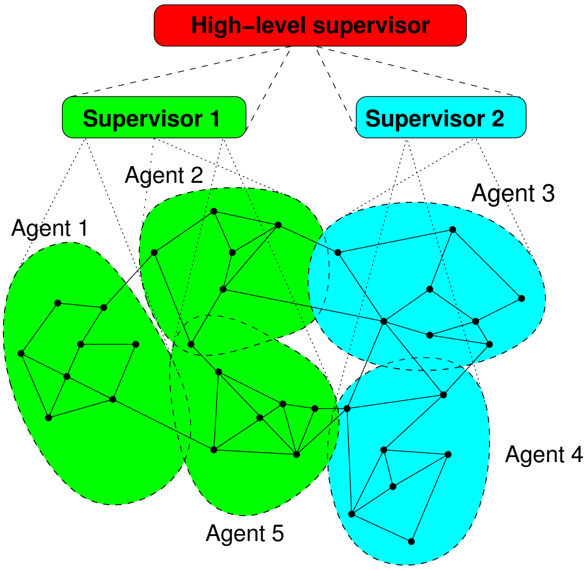

Figure 27: Multi-agent control framework.

7.4 Development of advanced multi-agent control strategies for multi-class traffic networks

Project members: M. van den Berg, B. De Schutter, J. Hellendoorn

Sponsored by: NWO-CONNEKT

This project is part of a larger project "Advanced multi-agent control and information for integrated multiclass traffic networks" (AMICI), and aims at developing an innovative control theory specifically suited to the coordinated control of heterogeneous traffic flow. General control objectives are to optimize network efficiency, to minimize safety-critical traffic conditions, and to minimize societal impacts, by providing class-specific travel information and traffic control. We combine existing control design techniques from the fields of distributed and hierarchical control, supervisory control, model-based control, hybrid systems control and multi-agent control and apply them to the traffic control setting sketched above. These techniques will be used to obtain a structured control design method and adapt them to the typical characteristics of a traffic system.

Figure 27 illustrates the multi-agent control framework used in this project. The traffic network is divided in several possibly overlapping regions, each of which is controlled by a local control agent. The agents cooperate and coordinate their actions so as to contribute to the reliable and robust operation and the performance of the entire system. Furthermore, we have one or more higher "supervisory" control levels.

In this project we also focus on optimization of the interaction between the urban network and the motorways, by dividing the networks into subregions. Besides being class-specific, integrated and coordinated, another characteristic is that the developed traffic control systems will be anticipatory (i.e., adaptive and predictive).

7.5 Validation methodology for fault-tolerant advanced driver assistance systems

Project members: O.J. Gietelink, B. De Schutter, M. Verhaegen, J. Ploeg (TNO Automotive)

Sponsored by: TNO-TRAIL

The main objective of this project is the development of a methodology for the validation of Advanced Driver Assistance Systems (ADASs). Examples of ADASs are adaptive cruise control (automatic distance keeping), collision warning systems, and pre-crash systems. An ADAS uses environment sensors (e.g. radar, laser, camera vision), electronic control functions, and actuators (brake-by-wire, steer-by-wire) to recognize critical traffic situations, give an appropriate warning to the driver, or react autonomously. In the development process of ADASs a number of challenges still lie ahead. The growing number of intelligent vehicle control systems and their interaction causes an increasing complexity of the control architecture, whereas the demand for reliability and safety of these systems has increased. Design and validation of these systems, especially regarding safety and reliability, therefore requires a growing effort in the product development process of these systems.

To improve the robustness and fault management of ADASs, often measures such as redundancy and fault-tolerant control systems are implemented. A fault management system can detect faults in e.g. radar sensor, communication systems or actuators (brake, throttle) and react accordingly. Currently, simulations and full-scale prototype tests on a test track are used to validate an ADAS. Simulations are however often not reliable enough, and test drives can be dangerous, difficult to analyze and difficult to reproduce. An efficient methodology is thus required for analyzing the reliability of the system. For this purpose TNO Automotive has developed VEHIL (VEhicle Hardware-In-the-Loop), a laboratory for the development and testing of intelligent vehicles. The VEHIL concept allows for conducting experiments on ADASs in a laboratory environment. Figure 28 gives an impression of a VEHIL test. Within this project the focus lies on the validation of the robustness and fault management of the ADAS control system using VEHIL.

Figure 28: VEHIL laboratory setup.

8 Physical imaging systems

The research activities of DCSC cover the application of (newly developed) methods and tools for modeling, measurement and control to practical problems in various fields of physics. One of the target application domains is formed by physical imaging systems. It is shown how a quantitative model-based approach, accompanied by statistical experimental design, allows precise measurement of the atomic structure of materials from electron microscopy images. Furthermore, optimal statistical tests are developed for the detection of neural activity by means of functional magnetic resonance imaging. We also apply modern control strategies to adaptive optics systems, with emphasis on ground-based telescopes.

8.1 Towards quantitative structure determination through electron microscopy

Project members: A.J. den Dekker, S. Van Aert (University of Antwerp), D. Van Dyck (University of Antwerp)

Sponsored by: KNAW

As scientists manage to control the structure of materials on an ever finer scale, more and more materials are being developed with interesting properties which are mainly related to their nanostructure. Parallel to this, one sees an evolution in solid-state theory where materials properties are increasingly better understood from first principle theoretical calculations. The merging of these fields will enable materials science to evolve into materials design. In order to correlate real properties with theoretical simulations, characterization methods in the future need to be able to determine atom positions in aperiodic structures with a precision of the order of 1 pm. Electron microscopy has this potential. From all possible imaging particles, electrons are the best candidates since they interact most strongly with matter to provide local information on atomic scale. However, the goal is not yet reached. Thus far, the technique has mostly been based on a qualitative basis, mainly as a result of the strong and hence complicated interaction of the electrons with the material. However, the directly interpretable resolution is no better than near-atomic (ca. 0.2 nm). For the future, this will be totally insufficient. To meet the future requirements, the electron microscopy images should be interpreted quantitatively instead of qualitatively. It is our goal to show that the interpretation of the images could greatly benefit from a quantitative model-based approach (in which statistical parameter estimation plays a crucial role) accompanied by quantitative statistical experimental design. The final objective is to develop a reliable quantitative electron microscopy method and an accompanying methodology for experimental design, which allow one to determine coordinates of the projected atomic structure with the required precision.

8.2 Optimal statistical analysis of functional magnetic resonance data

Project members: J. Sijbers (University of Antwerp), A.J. den Dekker, A.M. Van Der Linden (University of Antwerp), D. Van Dyck (University of Antwerp)

Sponsored by: FWO

Functional Magnetic Resonance Imaging (fMRI) is a relatively new technique for functional imaging of the brains, or the detection of active regions within brains under a variety of experimental setups. By means of a series of functional MR recordings during which a task model is applied, the aim is to find the hemodynamic response in order to constitute a statistical parameter map (SPM) of significantly active regions for each experimental setup.

Nearly all signal processing methods currently applied to fMRI data, such as construction of an SPM, are developed for gaussian distributed data. fMRI images, however, are not gaussian but Rician distributed. An important goal of our research is the development of statistical tests that account for the true, underlying data distribution. Previous research has already demonstrated that estimation of parameters from MR images may be improved significantly in case the incorrect assumption of gaussian distributed data is no longer retained but the correct (Rice) distribution of the data is taken into account. Therefore, it is expected that also this research will prove its value for the computation of SPMs.

Furthermore, a new technique will be developed that exploit spatial correlation of functional active regions within the image.

8.3 Control for adaptive optics

Project members: M. Verhaegen, K.J.G. Hinnen, N. Doelman

Sponsored by: TNO-TPD

Adaptive optics (AO) is a technique to actively sense, estimate and correct the wavefront distortions that are introduced in a light beam as it propagates through turbulent media [21, 28]. One important application is to counteract the effects of atmospheric turbulence in ground-based astronomical imaging, which results in a considerable improvement of the image resolution (Figure 29). Nowadays, most of the leading ground-based telescopes are equipped or being retrofitted with some kind of AO system. In this project we focus on the control aspects of adaptive optics. Our ultimate goal is to develop innovative control strategies for AO in general, with a main emphasis on systems dedicated to ground-based imaging.

The current generation of AO systems are often based on static control algorithms that are implemented as explicit matrix multiplications. These algorithms are usually derived from physical insights. The goal of this project is to apply modern control strategies to AO, which take into account the dynamics of the wavefront sensor, the deformable mirror and the turbulent atmosphere. The control of large AO systems poses a number of interesting research problems:

- **Modeling the disturbances, i.e. the wavefront distortions introduced by the turbulent atmosphere** In order to apply modern control strategies, a model of the disturbance is required. The main challenge is to model both the temporal as well as the spatial correlation of the wavefront distortions over the telescope aperture plane.

- **Development of an algorithm to predict the wavefront distortion**
The wavefront sensor inherently introduces a delay. Therefore it is desirable to introduce a predictor to estimate the current wavefront distortion. To this end an accurate model of the distortions is required.

- **Dimension of the control problem**
Current AO systems incorporate a few hundred to about one thousand sensors and actuators. The wavefront corrections have to be applied in real-time with a frame rate in the order of a few hundred Hertz, which imposes considerable demands on

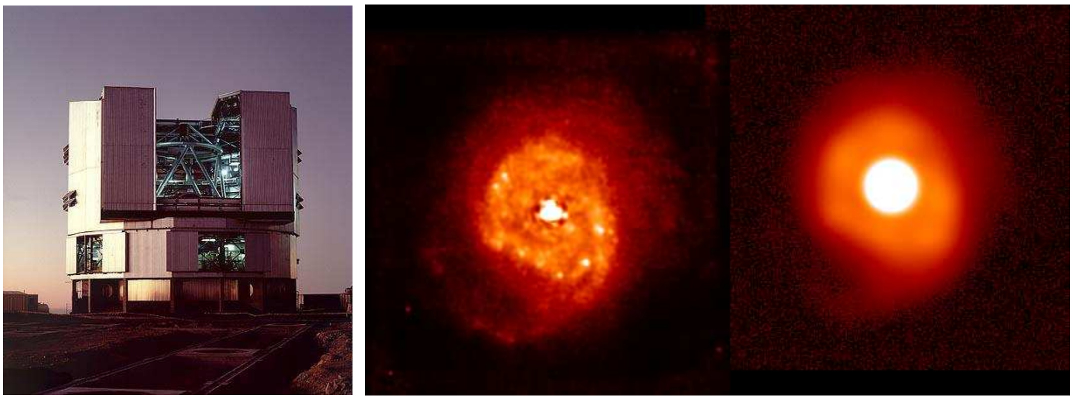

Figure 29: (left) Paranal Observatory, “Credit European Southern Observatory (ESO)” (right) Image of a galaxy with and without AO compensation “Credit Canada, France, Hawaii Telescope (CFHT)”

the computational power. This issue will become more and more important since the number of sensors and actuators of future AO systems is expected to increase. As the algorithms become more complex it may be necessary to consider distributed control.

- **Non-linearities in the wavefront sensor and deformable mirror.**

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