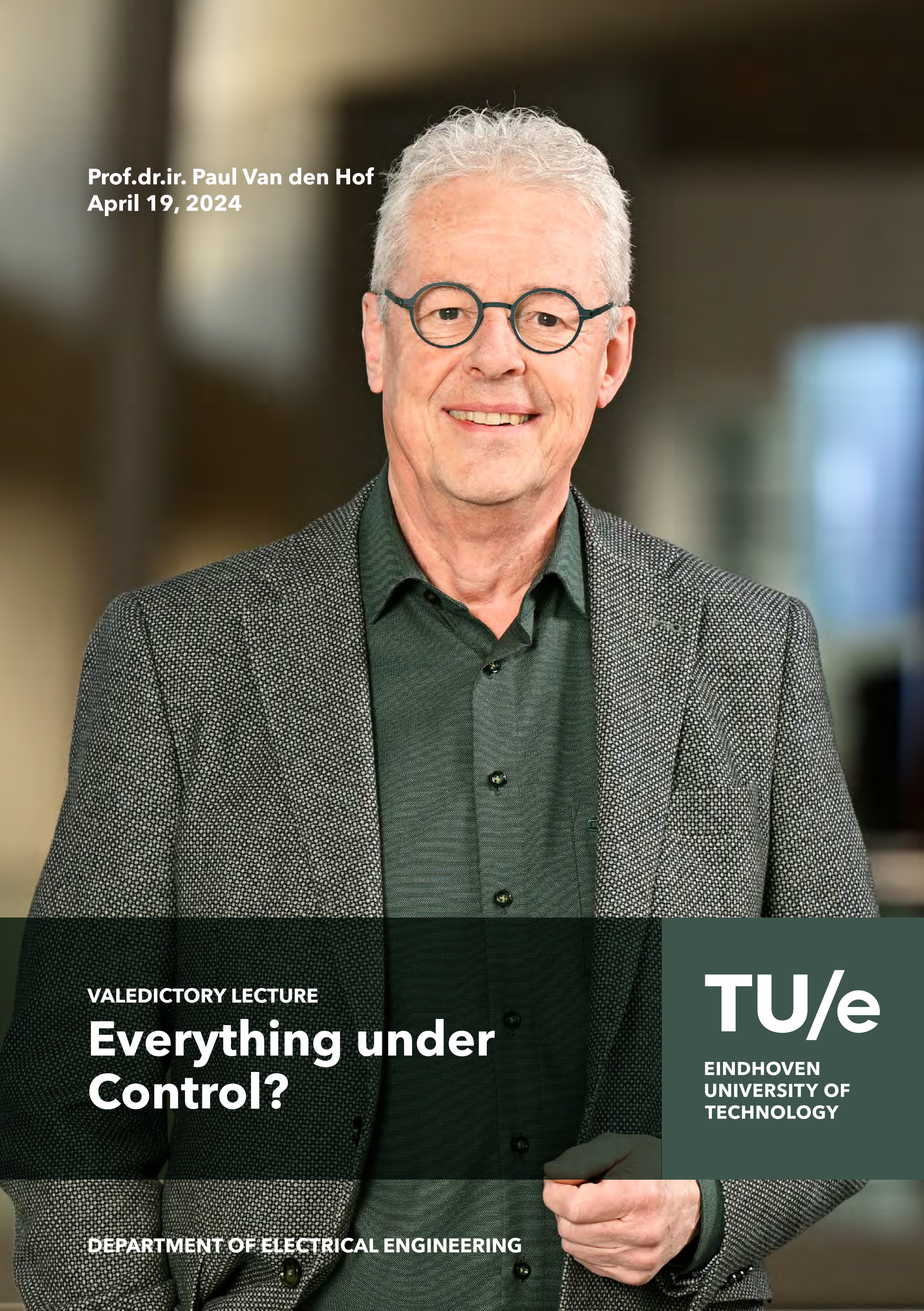

Prof.dr.ir. Paul Van den Hof
April 19, 2024

VALEDICTORY LECTURE

Everything under Control?

TU/e
EINDHOVEN
UNIVERSITY OF
TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING

VALEDICTORY LECTURE PROF.DR.IR. PAUL VAN DEN HOF

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Introduction

Mevrouw de Rector Magnificus, leden van het College van Bestuur, collega's, studenten, familie en vrienden, beste toehoorders,

In de periode van 41 jaar die ik werkzaam ben geweest in een universitaire omgeving, is er in die omgeving veel veranderd. Een van de aspecten daarbij is het internationale karakter dat het werk meer en meer gekregen heeft. Ik hoop dat u er begrip voor heeft dat ik mijn rede voornamelijk in het Engels zal uitspreken.

Slightly more than 41 years ago, I received my Electrical Engineering diploma here in this hall. It gives me great pleasure to speak about the journey that I took through the fascinating world of an academic career in the domain of systems and control. Over the next 40 minutes or so, I will illustrate some of the highlights over the years, reflect on my experiences, collect some messages, particularly for the younger generation, and, of course, also reflect on the question in which sense I was always 'in control'.

The position of a professor is, to a large extent, an independent position in which individual motivations and external opportunities, as well as group responsibilities, are important drivers of the activities that are undertaken. In this sense, this valedictory lecture is also a way to be accountable to the university, the government and society concerning my contributions over so many years.

After receiving my diploma in Eindhoven and starting a PhD trajectory here, I moved to Delft University of Technology in 1986, where I became an assistant professor in the Mechanical Engineering Systems and Control group of Okko Bosgra. My first position as full professor was in the Department of Applied Physics of TUD in 1999, after which I returned to the Department of Mechanical Engineering in 2004 to lead the new department named Delft Center for Systems and Control, a university-wide merger of three systems and control groups in Electrical Engineering, Mechanical Engineering and Applied Physics. In 2011, I responded to a call from Eindhoven University to return to my alma mater to take up the leadership of the Control Systems group in the Department of Electrical Engineering.

What I would like to do in this valedictory lecture is to take you through some aspects of the discipline of systems and control and, in particular, the identification or data-driven modeling problem, then highlight a few of the major research programs that I have been involved in. I will then reflect on the positioning of our discipline as well as on some university initiatives and education and will add reflections on the life of an academic.

Systems & control and system identification

Systems and control is a fascinating domain of science and engineering. With a generic language for modeling dynamic systems, irrespective of the discipline in which they originate (electrical, mechanical, thermal, etcetera), as well as the tools for mastering their behavior through (feedback) control, the field has been a prime ingredient of engineering systems for a number of decades already.

The domains in which control aspects play a role are numerous, including industrial process systems in petrochemical and chemical production plants, power grids and power distribution networks, climate control systems in buildings, mechatronic positioning systems and robotics, automotive systems, infrastructure systems (such as water distribution networks), and biological and physiological systems. The common phenomenon being that the relations between relevant variables in the system are given by differential equations, implying that the systems exhibit dynamic behavior, i.e., variables at a particular moment in time are dependent on other variables in the past.

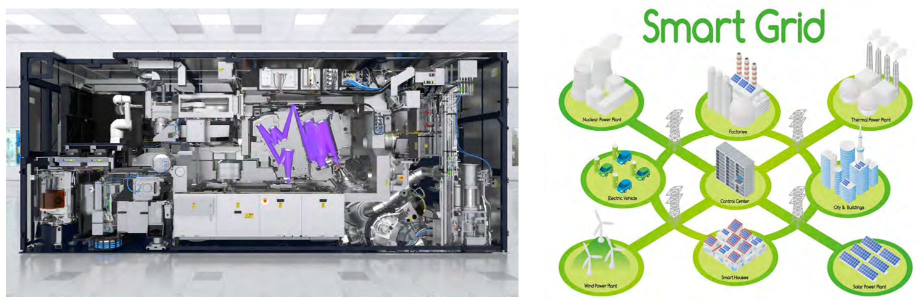


Figure 1. Examples of dynamic systems. ASML's lithography machine (left), smart grid[1] (right).

The exploitation of feedback, as one of the prime cornerstones of the systems and control domain, allows systems to perform at scales of accuracy that are far beyond the accuracy specifications of their components [11]. This fabulous concept is one of the crown jewels of the system and control domain and distinguishes

[1] smartcitiesworld.net

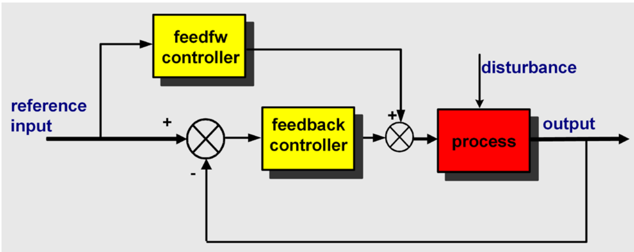


Figure 2. Classical control system.

the field from disciplines like computer science and artificial intelligence (AI). Other central ingredients are the handling of uncertainties and the capability of performing dedicatedly designed experiments.

Control technology is one of the prime reasons why ASML lithography machines are able to 'write' patterns on wafers and actually build 3D structures on them with a line thickness of 3 nm and overlay errors of less than 1 nm. And to do so with an incredible speed, illuminating around eight chip-areas per second. The basis of this controlled operation is an accurate understanding of how the machine behaves and how it responds to external inputs and disturbances, formulated in terms of a model of the system.

Constructing models is one of the cornerstones of the control domain. Finding accurate models of system dynamics is usually a tedious task in which both insights into first principle relations, such as the laws of mechanics and physics, and data from experiments and normal machine operations play an important role.

As a student of Pieter Eyhoff, my first entry into the field of control had a strong emphasis on the data-driven modeling part, referred to as system identification [5]. Building accurate models from (input and output) data from dedicated experiments was a challenging problem for which the required computational resources gradually became available in the 1970s and 1980s. It became the subject of my MSc and PhD theses and, although I later extended my activities to the broader field of model-based control and optimization, the system identification problem remained the one closest to my heart.

THE SYSTEM IDENTIFICATION PROBLEM

The system identification problem comes down to estimating a model of the dynamic system G, characterized by a differential equation, on the basis of time series measurements of input and output variables. A classical distinction between experiments is given by the open-loop and closed-loop settings. In the latter case, a feedback controller is present that affects the input to the system. The concerned variables can be scalar-valued (single-input single-output) or multivariate (multiple-input multiple-output).

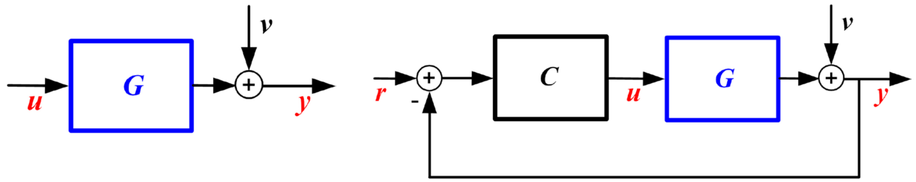


Figure 3. Open-loop system (left) and closed-loop system (right) for identification.

Important aspects to be addressed are:

- the selection of appropriate model structures to represent G, as well as the disturbance characteristic of v.
- the estimation of accurate models with minimum bias and variance.
- the validation of estimated models.
- the design of optimal experiments.
- the specification of model uncertainty bounds.
- the estimation of models that are goal-oriented, i.e., particularly fit for a specific use, e.g., to serve as a basis for control design.
- the development of accurate and effective algorithms.

The basis for this work has been the seminal contribution of Lennart Ljung [10], who shaped the area with clearly defined concepts, basic tools and algorithms.

In what follows, I will briefly highlight five major research lines/programs that I got intrigued and challenged by over the several years, including the most recent research on identification in dynamic networks that is still under development.

Orthogonal basis functions

One of the identification problems that attracted my attention in an early stage, was the development of effective model structures for linear systems in the form of orthogonal basis functions. The prime question is:

> "Can we come up with an effective model structure that can represent the unknown system with only a small number of parameters while being computationally attractive?"

Initiated in 1990 by Peter Heuberger, then a PhD student, and his advisor Okko Bosgra, I got involved in this research and found it an intriguing topic for further exploration. The basic idea was an attractive generalization of the pulse basis, the Laguerre basis and the Kautz basis, which are all more or less driven by some prior chosen dynamic information in terms of a pole location. This phenomenon could be generalized to any number of poles, thereby allowing general prior information on the linear dynamical system to be modeled, to be included in its basis, resulting in a series expansion of the system with a very high rate of convergence. Actually, the more accurate the prior information, the faster the rate of convergence of the series expansion becomes. The resulting Hambo-basis functions appeared to be a very attractive model structure for constructing model sets for identification, not in the least due to the fact that the resulting linear parametrizations would typically lead to convex optimization problems in identification. All the attractive properties of the FIR (finite impulse response) models are actually maintained while allowing a wider range of dynamics to be included. The underlying system theory for constructing and analyzing the properties of these basis functions appeared to be extremely rich.

The research work covered a major part of the 1990s, with the development of the basic theory and the subsequent use of the basis functions in model uncertainty modeling, frequency domain identification, reproducing kernels, realization theory and even transformation theory. Meanwhile, fruitful cooperations in this domain were started with international colleagues, including József Bokor, Bo Wahlberg, Hakan Hjalmarsson, Zoltán Szabó, Brett Ninness and Tómas Oliveira e Silva. After the initial idea and plan put together in 1995 by Peter Heuberger, Bo Wahlberg

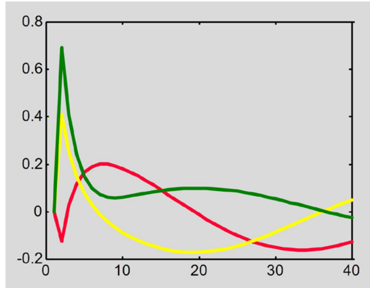


Figure 4. Three basis functions as an example for building up the pulse response of a system.

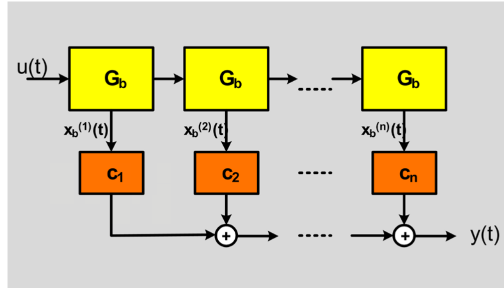


Figure 5. Generalization of a tapped delay-line with all-pass function G_b.

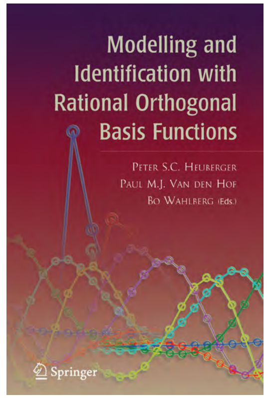


Figure 6. Springer book Heuberger, Van den Hof and Wahlberg (2005).

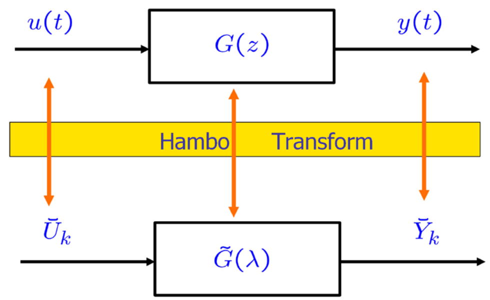


Figure 7. Hambo transform as a generalized transform of signals and systems.

and myself, it took us ten years to publish an edited Springer book [8] collecting the major contributions from that time period. It was a great endeavor to publish this, and highly successful as it is still a basic reference for many works related to generalized orthonormal basis functions in dynamic modeling.

The long-term cooperation with our Hungarian colleagues in the SZTAKI institute, led by József Bokor, should be mentioned in particular here as an important source of inspiration.

Also, after the publication of the book, the developments continued and the basis functions were effectively used in e.g., model uncertainty bounding, linear parameter-varying modeling, generalized transform theory, variance analysis, and kernel generation in machine learning and Bayesian estimation. An important message from the book, as stated in its introduction, formulated by Bo Wahlberg, is:

> "Almost all of what you can do using FIR models, you can do better for almost the same cost using generalized orthonormal basis function (GOBF) models!"

Identification for control

In the course of the 1980s, it was realized more and more in the community that estimating 'exact' or consistent models from data was probably not always the best paradigm to follow for evaluating identification methods. This also resonated in the engineering world, where the availability of useful models, rather than 'exact' models, appeared to be most important. And useful then needs to be interpreted in terms of 'relevant for its intended use'. The contribution of Wahlberg and Ljung [17] served as the starting point of assessing the approximative properties of estimated models.
As models are frequently used to serve as a basis for model-based control design, the follow-up question was: how to identify approximate models that are best to serve as a basis for robust control design? This appeared to be a very rich domain for exploration and became one of the popular research topics of the 1990s. It involved many different aspects, including:

- closed-loop identification of approximate models.
- model uncertainty quantification.
- iterative methods of identification and (robust) control.
- least-costly experiment design.
- data-driven controller tuning.

With the PhD thesis work of Ruud Schrama [14], we entered into this area, followed by a sequence of PhD projects all addressing different aspects of this new paradigm. One of the important new insights was that for estimating the best model for control, one would need to use closed-loop data of the process, which should be controlled by the controller yet to be designed. Obviously, this is a chicken-and-egg problem for which an approximate solution can be found by applying iterations. The new approach to this problem appeared to be a new version of adaptive control in which the typical lack-of-robustness problem of adaptive control was circumvented by a flexible mechanism for deciding when to iterate, i.e., when to update the model and/or controller.

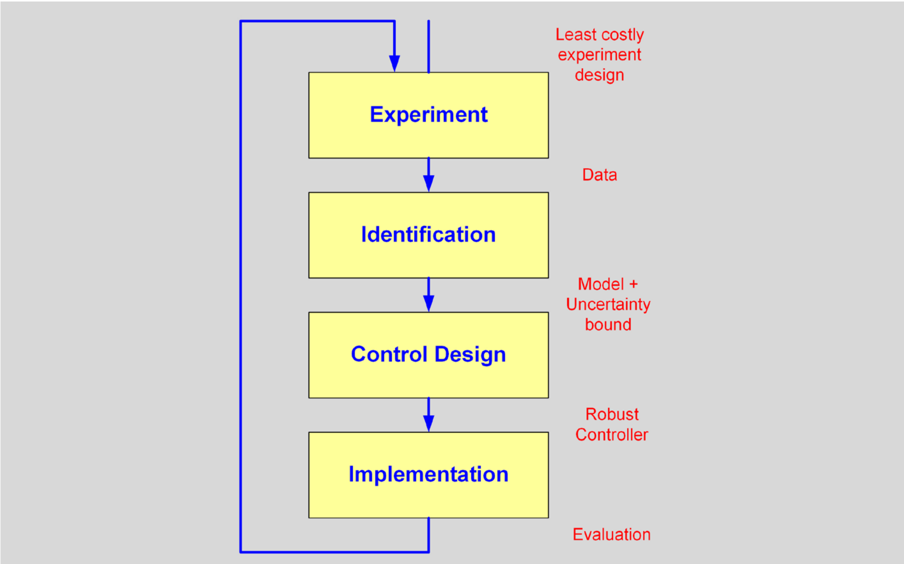


Figure 8. Iterative scheme of identification and control.

In a further generalization of this concept, extensions were made to include robust control methods on the basis of nominal models plus probabilistic model uncertainty bounds, as well as on the design of least-costly experiments that are sufficient for estimating models with sufficient accuracy for the particular (control design) application at hand.

With these developments, the concept of *learning* became more pronouncedly integrated into control design and experiment design became an important degree of freedom in actively generating process data that explores the important dynamic properties of the underlying system.

Overview accounts of this development have been given in [1] and in the survey paper by Michel Gevers [7]. However, as a community, we failed to prepare a solid textbook on this highly interesting topic. And now, 20 years later, this still feels like a missed opportunity, particularly in view of the current explosion of interest in data-driven control, where there is a serious risk that, in the overwhelming number of publications available, research achievements from the past are overlooked.

Concerning my own involvement in this research line, my efforts were reduced around 2005. While funding for this research used to be available through different resources (Philips NatLab, Philips Lighting, STW, NWO, TUD), these opportunities seemed to diminish. In my personal role, focus shifted towards setting up new courses in the Department of Applied Physics at TUD and bringing three systems and control groups together as TUD's new Delft Center for Systems and Control. A stronger appeal was made to develop my managerial skills. At TU/e, this research line continued through the work of then-PhD student Tom Oomen, who developed this further into successful applications in the domain of mechatronic systems.

After an intermezzo of several years, we managed to get a European project together to explore the potentials of the developed identification for control insights in an industrial setting, particularly in an (industrial) environment in which experiment costs are an important aspect and limitation.

Autoprofit

A dedicated use of data from process operations is particularly relevant in the process industry, where experimental data is scarce and dedicated experiments can be expensive. At the same time, the most commonly used control technology for larger-scale plants (model-based predictive control, MPC) was and is lacking a mature technological component for automated maintenance of the controllers. Handling unexpected events or a simple lack of understanding of what the complex multivariable control system is doing make process operators skeptical, leading them to switch off the control system and return to manual operation, with the consequence of a loss of efficiency and high costs of re-commissioning the controller. In order to develop methods and tools for an advanced operator support system that can automatically maintain a model-based control system under changing circumstances and uncertainties, we brought together a consortium of university and industrial partners that would address this challenging question.

With teams from Delft, Eindhoven University of Technology, KTH Stockholm and RWTH Aachen and industrial partners from ABB Sweden, (petro-)chemicals and energy company Sasol from South Africa and mining company Boliden AB from Sweden, we set up an EU-FP7 project that I was very happy to coordinate from

Figure 9. Leaflet of EU-FP7 project Autoprofit.

2010 to 2014. To make a serious appeal to our industrial partners, we selected the acronym AUTOPROFIT, standing for '**A**dvanced A**uto**nomous Model-Based O**per**ation **of** **I**ndustrial Process Sys**t**ems' (2010-2014).

The project targeted the development of a smart model-based operation support technology that enables control and model calibration/maintenance at a higher level of autonomy through

- continuous online data-driven performance monitoring,
- automatic detection of performance degradation,
- assessing the need for a model/controller update,
- acquiring the necessary data for performing this update,
- in a way that economic costs and benefits are continuously balanced.

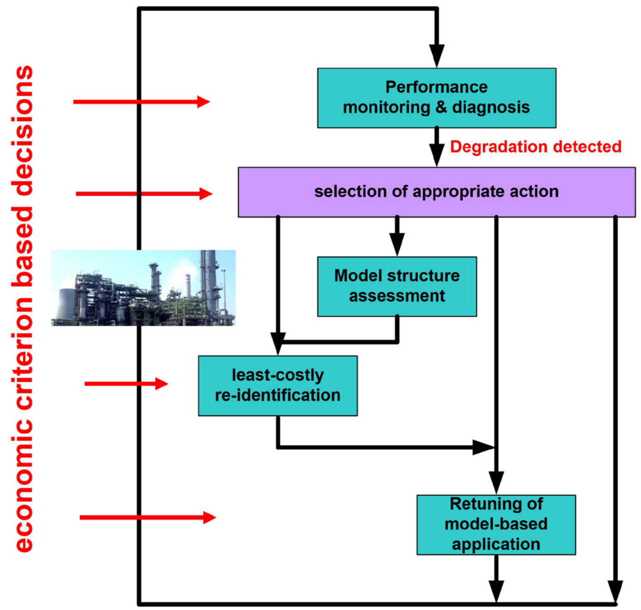


Figure 10. The Autoprofit loop of autonomous model-based operations, driven by economic criteria.

Highlights of this project, as reported in [12], include the development and assessment of the paradigm of designing least-costly experiments to obtain information from the process behavior without 'disturbing' the process too much.

This information can then be geared towards either (a) performance assessment and diagnosis; is the plant still operating according to specifications or is performance deteriorating and, if so, what is the cause of this? or (b) re-modeling of the changed plant characteristics.
This also included an experiment design approach, developed by the KTH team, to use the signal constraint space, typically present in an MPC controller, as a design space for allowing signals to be exploited for data informativity (MPC-X). Additionally, new tuning methods for controller tuning were developed and implemented and explorations were started to include aspects of nonlinear modeling in the paradigm through the use of linear parameter-varying (LPV) models.

The developed technology was tested on an FT depropanizer at Sasol Synfuels' Secunda site in South Africa, where PhD students and postdocs that were involved in the project spent a couple of weeks working on the actual implementation and testing of the tools.

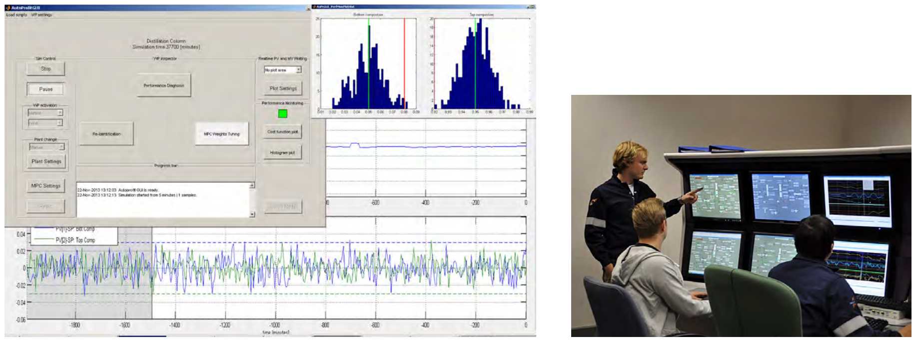


Figure 11. PhD students implementing the new operational tools on a depropanizer plant at Sasol's Secunda site, South Africa.

A second implementation, focusing on the least-costly experiment design aspects, was made on a zinc flotation plant at Boliden Mineral's Garpenberg mine in Sweden.

Figure 12. Part of Sasol's production site in Secunda, South-Africa.

An interesting observation at the end of the project appeared to be the following. In the closing workshop with a number of relevant stakeholders from industry and academia, it came to the table that it would actually be very attractive if the operating support system would not only suggest/implement the suggested actions on the actual plant but also explain to the operator why these actions are taken. This would allow the operator to build trust in the system and would prevent him/her from returning to manual operation in the case of unexpected situations. The suggestion to let the controller 'speak in English' to the operator points to a highly relevant and nontrivial challenge that, as far as I know, has not been addressed in the literature so far.

While the Autoprofit project was highly successful and was rated as 'Excellent' by the EU after the final report, there appeared to be no opportunity to follow up on this development that had actually only just started. Shifting objectives in EU programs and calls made it impossible to obtain support for continuing the consortium. In this respect, we were definitely not in control.

Reservoir engineering

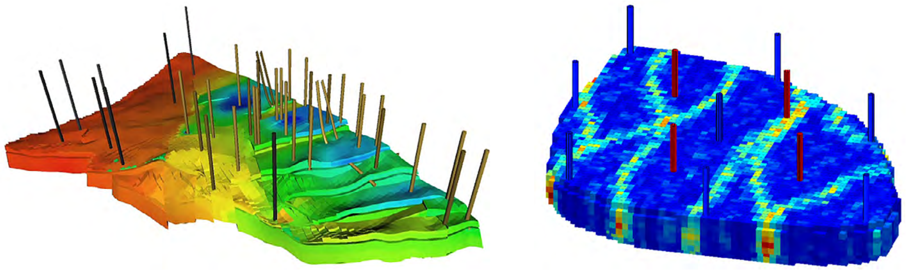


Figure 13. Hydrocarbon (oil/gas) reservoir in a geological structure (left) and a smaller-scale simulation example (right) with indicated permeability patterns and injection wells (in blue) and production wells (in red).

In a different domain, a long-term and challenging research program was executed on the development of model-based operational strategies for optimal exploitation and life-cycle management of hydrocarbon reservoirs. During the period 2003-2017, several generations of PhD students were involved in a consortium with contributing partners from TUD/DCSC (and later TU/e-CS), TUD/Applied Earth Sciences, TUD/Applied Mathematics and Shell International Exploration and Production, supported by Shell and the ISAPP (Integrated Systems Approach to Petroleum Production) institute, including TNO.

Initiated by Cor van Kruijsdijk and Jan Dirk Jansen (TUD/Applied Earth Sciences and Shell), an innovative merger was made of expertise from both the applied earth sciences perspective and the systems and control domain, with Okko Bosgra and myself representing the latter domain.

The main challenging problem was to develop operational strategies for secondary recovery in which additional injection wells are drilled in a hydrocarbon reservoir to provide water pressure to the subsurface reservoir for displacing the oil towards the location of production wells. The dynamic behavior of such a reservoir is typically described by the spatially distributed permeability field, on which information is only available with high levels of uncertainty. With the introduction of smart wells, the wells can be equipped with extensive sensing equipment, providing additional data for monitoring the reservoir, e.g., by estimating model parameters and the location of the oil-waterfront in the reservoir. This also allows the implementation of model-based control and optimization methods to operate the reservoirs in such a way that economic revenues are optimized over their life cycle. In such a control system, the valves of the water injection and oil-producing wells are controlled. In a reactive strategy, no model information is used, the valves in all wells have a constant value, and production wells are shut in (closed) once water is being produced instead of oil. In a model-based approach, an optimal control method is implemented that controls the valves in both the water inlet and the oil production wells so as to maximally use the water pressure to maximize production at all wells over the lifetime of the reservoir, typically in the range of 20 years. Combining this strategy with data from the smart wells led to the development of a closed-loop reservoir management system, as sketched in Figure 14.

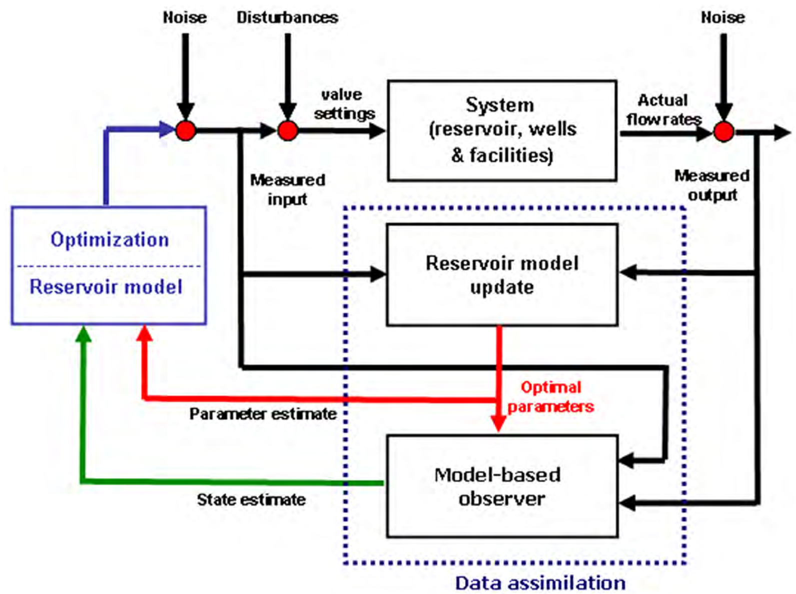


Figure 14. Closed-loop reservoir management system.

One of the challenges in this work was the development of low-dimensional models that accurately represented those properties of the reservoirs that were most important for the optimization process. In this sense, this problem area fully matched with the 'identification for control' research, including the handling of appropriate uncertainty bounds on the models. Alongside the many published journal papers and PhD theses, this multidisciplinary research was presented in keynote lectures at both reservoir engineering and control conferences, see e.g., Figure 16.

As one of the results, the exploitation of spatial-temporal functions for characterizing permeability patterns in the subsurface appeared to be very effective, see e.g., Figure 17.

Long-term support for this collaborative research gave us the opportunity to raise several generations of researchers/engineers with strong multidisciplinary skills, combining expertise from applied earth sciences and reservoir modeling with systems and control skills, including data analytics and dynamic optimization. Many of them found attractive jobs with our partners in this technology sector.

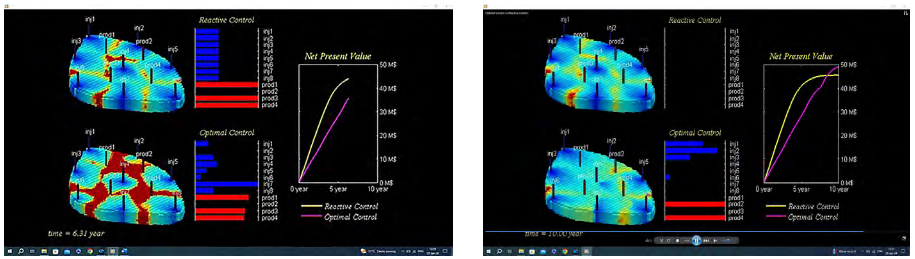


Figure 15. Simulation of an optimal control strategy[2].

[2] Implementation made by Gijs van Essen.

Figure 16. Keynote lecture at the Chinese Control Conference, Xi'an, P.R. China, 2013, with around 1200 attendees.

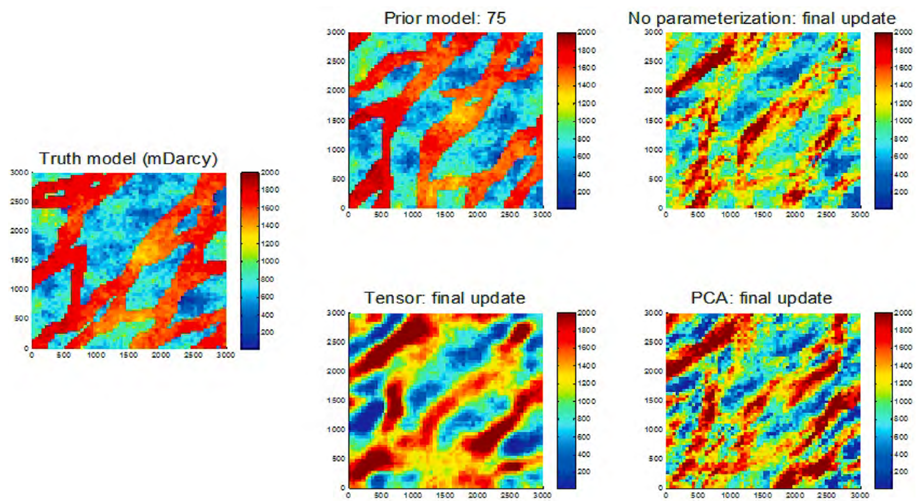


Figure 17. Representing permeability channels through spatial-temporal functions[3].

[3] Figure produced by Edwin Insuasty.

Dynamic networks

Around 2010, I saw an opportunity to return to my ‘home base’ in research, namely the system identification problem. Observing the developments in many engineering environments, it appeared that more and more of the systems that were being considered for control and optimization were growing in size, becoming more complex, spatially distributed and composed of (many) interconnecting subsystems. Consider e.g., a power distribution network with different power-generating units and consumers or a water distribution network, but also complex machines like ASML’s lithography machine, composed of many subsystems that, through their interconnections, all have their effect on the ultimate performance of the machine. Other examples include large-scale (petro-)chemical manufacturing sites and even the physiological behavior of the human body, where many subsystems interact for the control of glucose, temperature, blood pressure, etcetera.

The control community responded to this situation by developing alternatives to the classical centralized control approach in which a control action is computed and implemented typically at one location in the system. In decentralized and distributed control, the control actions are implemented locally and local controllers can potentially share information with each other so as to obtain globally optimal behavior. A natural question that comes to the table then is how to come up with a (data-driven) modeling paradigm that provides the relevant model information for these distributed controllers. In other words: how to identify particular components in dynamic systems that are actually composed of interconnected subsystems in which the subsystems can have either unknown or known dynamics. The latter situation is the case if e.g., human-designed controllers are part of the total system.

Starting from our knowledge on how to identify a system that is operating under feedback control, we started to develop a new paradigm for identification in dynamic networks. Concerning financial resources for this, revenues from industrially funded projects allowed me to fund this PhD research with internal funding. The additional benefit of this was that we were completely free in exploring new directions in a research team with PhD student Arne Dankers and co-supervisors Xavier Bombois and Peter Heuberger. The first sketches of a setup and the first research results were reported in 2012: which aspects play a role when detecting the topology/structure of the network from data and how to use our (classical) prediction error identification framework for identifying the dynamics of a single element in such a network? As a network setup, we had chosen what later became known as a module framework, interconnecting dynamical systems with a priori-defined inputs and outputs, i.e., a priori-defined cause-effect directions. This framework happened to be the most natural extension of the classical closed-loop identification problem towards more complex topologies [15].

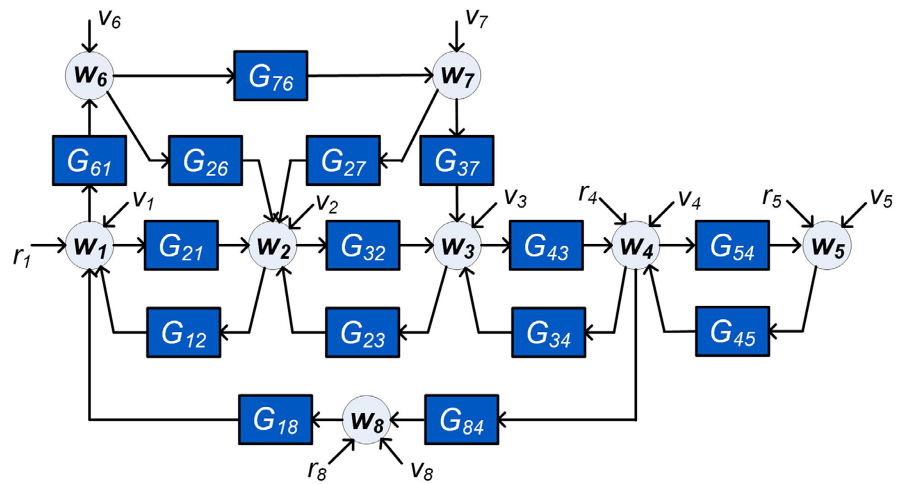


Figure 18. Prototype example of a module-based dynamic network.

After moving to Eindhoven in 2011, a second PhD student, Harm Weerts, took over from Arne Dankers in 2014 and developed a full framework for analyzing network identifiability. The research so far had indicated that there was a very rich domain of highly relevant open questions ahead of us, including questions like:

- Where to allocate sensors and actuation signals to reaching a particular data-driven modeling objective? Or, conversely, what are the limitations for a given set of sensor and actuation signal locations?
- How can methods for actual topology identification from data be developed?
- How can methods for single module and full network identification be developed?
- How to appropriately handle a wide set of disturbance characteristics, as e.g., reduced rank noise?
- How can the network paradigm be extended to interconnections without prior input/output directions?

This rich set of challenging open questions, together with some initial solution directions and results, was a strong asset in obtaining a personal ERC Advanced Research Grant in 2016 from the EU to further develop this technology. The research grant allowed me, for a period of six years, to fully focus on this research with a team of PhD students and postdocs. To list a few highlights in this research:

- The development of graph-based theory and tools for analyzing and synthesizing module/network identifiability.
- Extensive theory and algorithms for the identification of single modules and full networks.
- Data-driven methods for distributed control in networks.
- The development of an alternative framework for network modeling based on diffusively coupled (non-directed) networks.

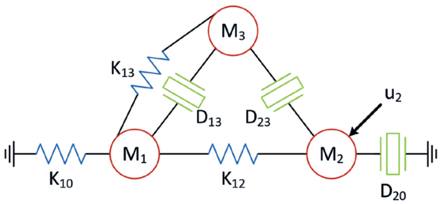


Figure 19. 2D mass-spring-damper system as interconnected network.

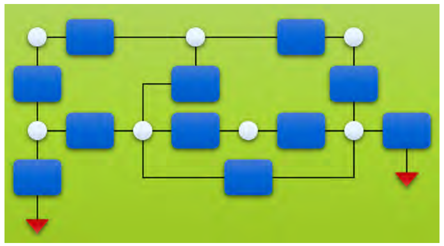


Figure 20. Diffusively coupled network [9] with non-directed interconnections.

One of the restrictions in our original choice of module-based network has been the causal input/output structure of the subsystems. The resulting graph that represents the network topology is a directed graph. However, in engineering systems, components that are being interconnected often do not have a prior input/output separation. The role of inputs and outputs appears as a result of a particular way of operating/driving the system. As a result of this prior chosen direction, a limitation is imposed on the type of data that can be used for modeling the system: when doing one experiment in which information is sent from left to right through the network and a second experiment in which information is sent in the reverse direction, the models representing the two situations are different because of different input/output choices. At the same time, we may expect the physical relations underlying the network to be the same and to not be dependent on the experiment done.

This mechanism is overcome when using diffusively coupled network models in which all interconnections are symmetric and therefore non-directional. The resulting graphs, representing the network, are non-directed. Rather than using state-space models or transfer function descriptions, this approach relies on polynomial or kernel representations. This insight very much appeals to and has been inspired by the behavior modeling of Jan Willems [18].

Over the years, the methods and tools have been applied to a select number of case studies, including leak detection in gas pipelines, printed circuit board (PCB) testing, brain network interconnectivity analysis on the basis of EEG signals, and distributed climate control systems in buildings. Extension of these case studies is foreseen and is currently being worked upon, e.g., in diagnostics problems in lithography machines in cooperation with ASML.

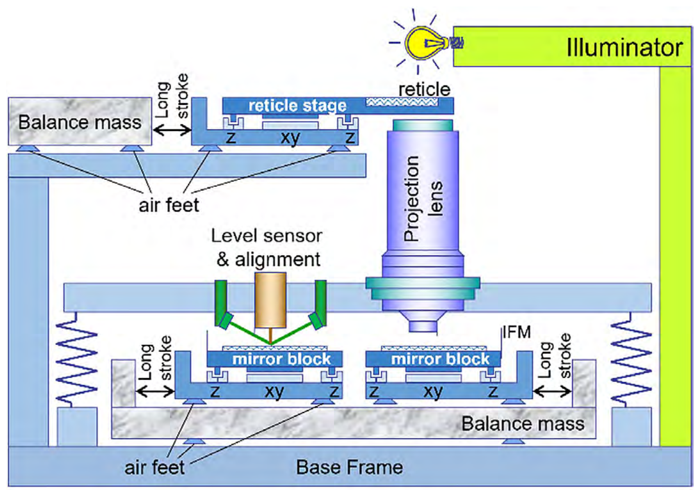


Figure 21. Schematic of the moving stage part of a lithography machine as an interconnection of subsystems.[4]

The problem: on the basis of sensor data at different locations in the machine, determining if a fault is occurring (disconnected cable, screw insufficiently tightened, change in dynamics) and diagnosing the location of the fault as fast as possible so as to reduce downtime of this 200 M€ machine.

[4] Figure from H. Butler, Position control in lithographic equipment, IEEE Control Systems Magazine, October 2011.

Starting in 2021, we also stepped into software development as a means to better communicate our results to the outside world and as a platform for effectively using the collection of methods and tools that have been developed so far. This has led to the MATLAB™ Toolbox SYSDYNET [17], with an attractive graphical and interactive user interface of which a beta version was released in 2023 and can be downloaded for free. For the continuation of the development of this toolbox, the EU has recently awarded a Proof-of-Concept Grant that, in the next 1.5 years, will allow us to also investigate the opportunities for developing this software into a mature product.

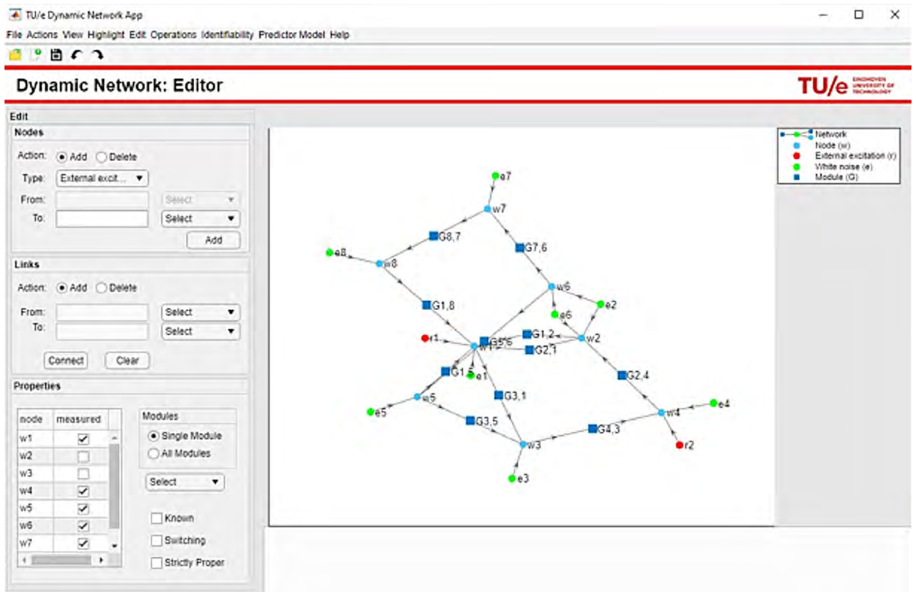


Figure 22. Interactive graphical user interface of the SYSDYNET app and toolbox for identification in linear dynamic networks [16].

This research line has turned out to be very attractive and successful so far. How important it will be for future developments still needs to be seen. Was this development actively planned for? Well, it did crucially depend on some arbitrary factors. Had I not had the saved revenues from industrially funded projects in 2010, this project would probably never have started. To some extent, this also shows the limitations of the control that we have over our own activities.

University initiatives

During my academic career, I was involved in several university initiatives of which I would like to mention the main impactful ones.

One of the major strategic and managerial moves was, at TU Delft in 2003, the merging of three systems and control groups into the Delft Center for Systems and Control (DCSC) as part of the Faculty of Mechanical Engineering. It became a department with strong international appeal. This challenging operation was also the initiating point for launching a new MSc program in Systems & Control as a response to the establishment of the BSc/MSc structure in our educational programs. It was a great opportunity to position the systems and control domain as a separate discipline with strong ties across traditional departments, such as electrical engineering, mechanical engineering, chemical engineering, applied physics, mathematics and computer science. This international MSc program was, and currently still is, built around three pillars: modeling of dynamics, control systems analysis and design, and data analysis. Since its establishment in 2003, many generations of students have been educated as systems and control engineers and have found their way into attractive jobs in industry, institutions and academia.

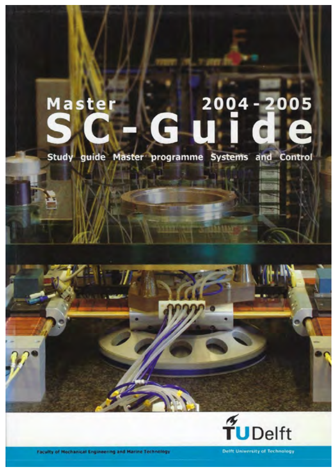


Figure 23. Study Guide MSc Program Systems and Control, 2004-2005.

Driven by the national cooperation in DISC, this MSc program was elevated to a 3TU program, with similar programs being offered in TU Eindhoven and U Twente. It has been very rewarding to see that both the TU Delft program, in 2010, and the TU/e program, in 2019, received excellent reviews from the national 'Keuzegids Universiteiten', leading to the qualification 'Top-Rated Program' in the national University Guide to Master's Studies in 2019.

Figure 24. Positioning of the 3TU Center of Excellence on Intelligent Mechatronic Systems, 2005.

In 2005, the three technical universities had the opportunity to make a serious investment in research, in research themes that were timely and in which solid cooperation could be established between the three TUs. Supported by the long-term cooperation that was already established in DISC, we managed to team up with the control groups of Delft, Eindhoven and Twente to prepare a proposal that was granted and led to an investment of 10 M€ over a period of five years. The result was the establishment of a Center of Excellence on Intelligent Mechatronic Systems within the scope of a program on High Tech Systems and Materials. As a result, several tenured academic positions could be created in the different groups of the three universities.

After my return to TU Eindhoven in 2011, I became part of the high-tech systems network and ecosystem in the Brainport Eindhoven area. With ASML as main central point, a fabulous ecosystem has been established with many companies involved in the realization of high-tech equipment. Although TU Eindhoven was connected to this ecosystem at a research group level, an institutional positioning

in the high-tech systems domain was absent. The start of the university 'Impulse' program in 2013, in which the Control and Mechatronics groups of Mechanical Engineering and Electrical Engineering teamed up, was the starting point for establishing the TU/e High Tech Systems Center (HTSC). With the participation of the Departments of Mathematics & Computer Science and Applied Physics, this center became the university signboard for research projects in cooperation with a wide spectrum of industrial partners. Led by Maarten Steinbuch and Katja Panke, it promoted a systems approach to the design of high-tech equipment. Additionally, it created awareness within TU/e that the high-tech systems domain is in need of a strong and well-organized university partner in the Brainport Eindhoven ecosystem.

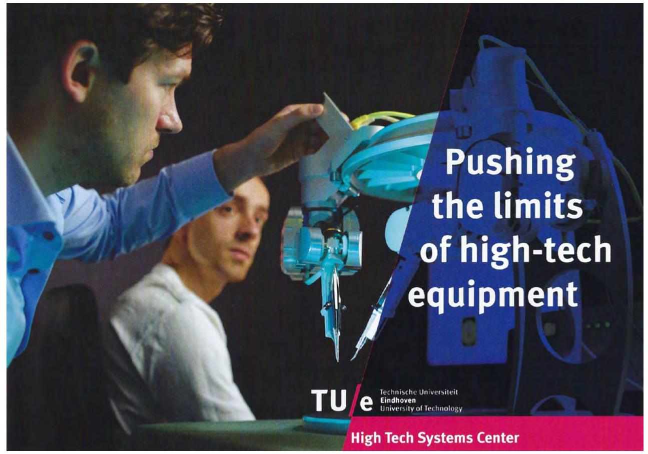


Figure 25. TU/e High-Tech Systems Center leaflet.

In 2019, an early-stage initiative was taken to position Eindhoven University of Technology more pronouncedly in the arena of artificial intelligence (AI). In order to support the unique opportunities and strengths of TU/e in this domain, as well as to foster potential links with industrial and institutional partners, a broad institute was launched: the Eindhoven Artificial Intelligence Systems Institute (EAISI). Rather than a narrower positioning of the AI field around data science and computer science, EAISI positions itself in particular on the interplay between AI and engineering systems. Being among the group of initiators of this institute, I was happy to contribute to the establishment of this wide setting of AI within TU/e and allow engineering departments such as Electrical Engineering and Mechanical Engineering, but also Industrial Engineering and Innovation Sciences, to fully participate in the development of smart data-driven methods for the engineering systems of the future. In this setting, the importance of humans as an intricate part of AI engineering systems has been recognized, as witnessed by the mission of the institute, formulated as:

> "EAISI aims to develop AI technology for real-time autonomous decision-making in engineering systems that interact with humans."

The current prime application domains of EAISI are in high-tech systems and robotics, health applications and smart mobility. While actively promoting and positioning TU/e research in this emerging field, one of the underlying objectives is to build an EAISI community at TU/e that crosses boundaries between traditional disciplines and departments and supports the development of new generations of AI-educated engineers. The recent start of a new MSc program in Artificial Intelligence and Engineering Systems (AI&ES), hosted by our Department of Electrical Engineering, has been an important step in this direction. This program has seven participating TU/e departments.

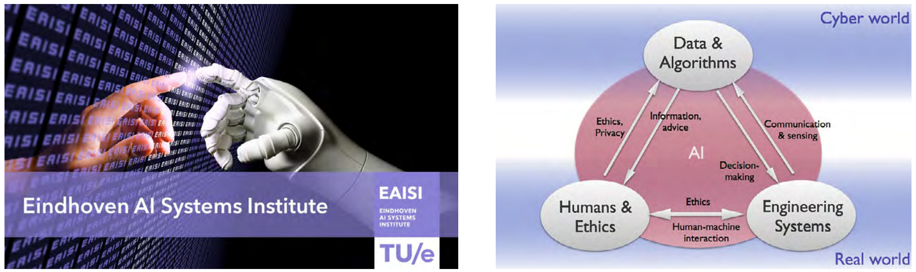


Figure 26. Eindhoven Artificial Intelligence Systems Institute, and its research positioning based on three pillars.

Positioning and prospects of the field

If we evaluate the current positioning of the systems and control field, we can only conclude that the field is alive and very much at the forefront of innovative developments in engineering systems. The systematic approach that is involved in the 'systems thinking' concept in engineering analysis and design problems is a key asset that has appeared to be highly valuable in industrial practice. For quite some years already, TU Eindhoven has had more than 100 PhD students actively working in the domain of systems and control. Of course, this cannot be seen as separate from its embedding in the Brainport Eindhoven area, with an incomparable number of high-tech systems companies and the leading role of ASML.
For many future developments of smart technology, systems and control aspects will be key and the challenges are numerous, see e.g., the reports on research agendas in Lamnabhi-Lagarrigue et al. [6] and more recently in Annaswamy et al. [2]. This includes climate change mitigation and adaptation, healthcare, smart infrastructure systems, electrification, robotics, smart production systems and biology.

On the data-driven modeling side, important steps forward have been made by introducing new concepts originating from machine learning, such as kernel-based regularization [13], into the modeling framework. In a rather simple extension, identification methods are revised to effectively trade bias and variance effects rather than aiming for minimum variance under zero (asymptotic) bias. Regularization techniques have also been instrumental in turning neural networks into attractive modeling blocks for estimating systems with non-linear dynamics in deep learning. Important attention is also given to building model structures for non-linear models that are motivated by underlying physical relationships between the variables. Utilizing the physical knowledge on which an engineering system is built will remain an important aspect in effective modeling methods.

There is a strong debate in the community now on whether models should be used as a basis for control design and decision-making or whether the models should be replaced by direct measurements (data) of the process. In my mind, models have the role of stored information from past experience, as well as of prior knowledge, obtained from a physical understanding of the underlying process dynamics. The crucial point of decision-making for the user will then be to assess whether information from the past is still in place and can be used or whether the system properties can change so drastically that any new experiment has to start from zero knowledge of the system at hand.

With the current explosive growth of and attention for AI, based on there being an abundance of data available, the systems and control domain is in a perfect shape to extend its concepts for control and optimization in order to reach out and contribute to the AI domain for the development of engineering systems with high levels of autonomy and learning behavior and in which humans will need to (be able to) interact with the technology. Consider e.g., drivers in (semi-)autonomous cars, people dealing with support robots, human operators dealing with smart industrial process instrumentation, or personalized health monitoring.

While there is some hesitation within parts of the systems and control community to explicitly link to developments in AI, I am happy that within Eindhoven, with the start of the EAISI institute, control has become an intrinsic part of the AI activities. Actually, three of the eight research lines of the EAISI roadmap [EAISI] have a clear control signature:

(a) Merging models and data in AI
(b) Decision-making for engineering systems
(c) AI systems engineering

Within EAISI, this is complemented with research lines on trustworthy data integration, certifiable, robust and explainable AI, computational AI hardware and software, augmenting intelligence, and democratizing AI. Teaming up between control people and AI experts can bring and actually is already bringing a boost to the development of smart engineering systems.
It remains to be seen, though, whether the popular term 'everything under control' will eventually be replaced by 'everything under AI'…

National and international collaboration

NATIONAL COOPERATION

The Dutch Institute of Systems and Control (DISC) unites all research groups on systems and control in the Netherlands. It is an effective network that has run a collective national PhD program for our PhD students since 1987 and that operates through weekly courses in Utrecht, summer and winter schools with international lecturers, and yearly Benelux Meetings for staff and PhD students.
I had the honor and pleasure of serving as its scientific director in the period 2005-2014.

The Dutch systems and control community is way larger than one would expect given the size of the country. This also holds for the number of Dutch researchers that are active in and highly recognized by the international community. And the DISC institute, through its activities, is also well-recognized internationally [11]. It is a strength of our national community and an asset in attracting international talent on all levels.

All through the past 35 years, DISC has taken responsibility for high-level PhD education and a scientific network environment for PhD students. In times in which universities have taken a varying and rather ambiguous position towards PhD education, the role of research schools like DISC has been unchangeably important.

disc dutch institute of systems and control

DISC had some particular successes in the past, including the establishment of the 3TU MSc program in Systems and Control (2004), the High Tech Systems Center of Excellence (2005, 10M€), and the recognition of DISC's PhD program as a NWO Graduate Program (2010, 800K€). Finance-wise, DISC is mainly operating on a very moderate financial budget, while lecturers that teach in the PhD program basically still teach 'pro deo'. This situation, which was quite natural back in 1987, appears very special now in 2024. It reflects the perceived prestige that is connected to lecturing in a DISC course.

I am very happy that, as a Dutch community, DISC has been able to attract the triennial IFAC World Congress in 2029 to Amsterdam, the Netherlands. This is the largest international conference in control, with around 3500 participants. It is the first time in the history of IFAC (International Federation of Automatic Control) that a World Congress will be held in the Netherlands, which was one of the founding countries of the federation in 1956. It will be a great opportunity to strengthen the position of the systems and control domain in the Netherlands, as well as to promote our national activities worldwide.

There are also a few critical remarks to be made on the national positioning of our scientific domain, particularly in relation to funding agencies. Contrary to many of our international colleagues, we have not been able to get our systems and control domain recognized as a domain that also goes beyond engineering applications and for which fundamental research is required to secure long-term innovations. The consequence of this is that virtually all national funding schemes require matching of available project budget with considerable contributions from industrial partners, leading to situations where the horizon for achieving applicable results remains relatively short. I hope that with the recently installed Netherlands Academy of Engineering, the voices that also promote the more fundamental part of engineering sciences can become louder.

INTERNATIONAL

The international working environment, with organizations like IFAC, IEEE and EUCA, is a highly inspiring environment. Being part of the international control community has brought an uncountable number of gatherings, inspiring discussions and enjoyable social drinks with colleagues and friends. In IFAC in particular, the single worldwide operating organization with 48 member countries, I have served in many capacities and over many years. Highlights have been the organization, together with Siep Weiland and Bo Wahlberg, of the 2003 IFAC Symposium on System Identification in Rotterdam and my role as IFAC Vice-President in the triennium 2017-2020, during which, under the leadership of Frank Allgöwer as IFAC President, the operational structure of IFAC was substantially modernized.

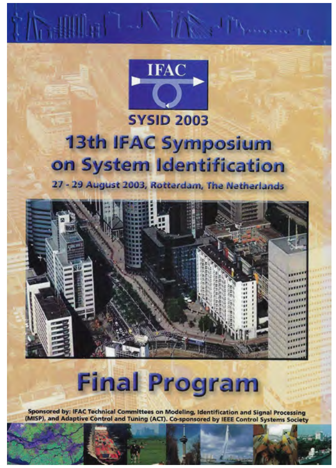


Figure 27. Final program book of IFAC's Symposium SYSID, Rotterdam, 2003.

The European Research Network on System Identification (ERNSI) was established in 1992 on the basis of an EU SCIENCE grant for research collaboration and was coordinated by Jan van Schuppen. Its yearly workshop has become an important place for gatherings of staff and PhD students of participating European research groups to present and discuss the developments in the system identification domain. After the European funding ended, the groups involved decided to continue the initiative and, with the current coordinator Bo Wahlberg, the workshop has established itself as a popular meeting point and is highly appreciated, particularly because of its informal status and ample room for discussions.

University life – life as an academic

THE BEST POSSIBLE JOB

Being a university professor is a fantastic job. Your prime task is to invest in your own knowledge and skills, work with bright and enthusiastic young people, collaborate with colleagues and friends from all over the world, teach, supervise and coach students in their development, develop your personal academic 'business' and continuously solve new challenging and intriguing problems. And on top of that, there is no boss to tell you what to do. The only downside of this is that nobody tells you when you have too much on your plate and that you continuously have to find the financial support to pursue your goals.

UNIVERSITY ON THE MOVE

In the 41 years of my academic career, university life has changed considerably, from what could be phrased as a rather static government department to a very dynamic organization of research and education where most of the budget for research comes from 'outside' and has to be gathered in competition. Systems for measuring academic performance have the tendency to emphasize quantity over quality, as a result of which the work pressure on young people entering the system has become very high.

The trend of giving young academics an independent position in the university from the start of their career rather than becoming an assistant to the full professor is a policy that I have supported wholeheartedly from the start. At TUD, I was a member of a strategic advisory group of the rector that laid down the contours of this (tenure track) system. However, there is also risk involved in this system if it is carried to the point that all young people also become financially separated from the group and, from the very start of their career, are fully responsible for attracting their own budget. Careful guidance, support from senior colleagues and teaming up with them require a strong group management aimed at collaboration, thus avoiding a 'everybody-for-him/herself' attitude.

While university groups have become individual 'business' units that are held accountable for their operations and their managers/workers are supposed to be academic leaders, business managers, researchers and lecturers at the same time, the adaptation process of the university organization to this situation could use an acceleration. One of the remarkable successes in my university life has been the establishment of an operational executive position at a HBO level in our group, which could take over organizational and operational tasks from scientific staff. It took me more than one year and repeated problematic discussions with HR to get this organized. It turned out to be a great success, given the fact that many groups are now making moves in that same direction.

IDENTITY AND UNIVERSITY VALUES

In the process of turning the university into an organization that is very active in exposing its activities to the outside world, in accellerating innovations, in positioning itself for attracting research budget and in attracting 'customers', the operation mode of the university's researchers is also affected. There is a stronger emphasis on (and need for) attracting externally funded research projects, most often in collaboration with industrial partners. While this provides great opportunities for researchers to work on industrially relevant problems and to transfer the results of scientific research into applicable tools and methods, it also has the effect that the university's research organization is gradually moving in the direction of a project organization with high attention to deliverables and deadlines, where the partners that provide the budget would like to have a large say in the activities undertaken. However, fundamental innovative research is often hard to fit into a scheme of predetermined deliverables with predetermined described results. A university is not a company and its employees should be encouraged to preserve the values of being a university and to defend their status as independent, self-confident university representatives.

EDUCATION

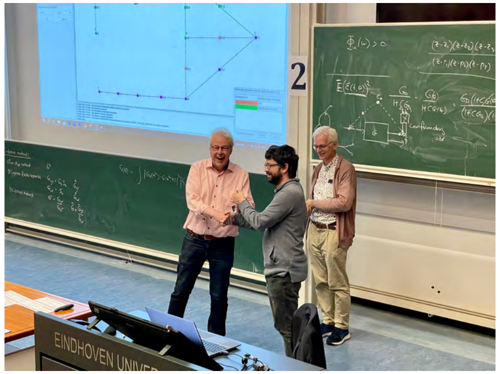


Figure 28. Symbolically handing over the chalk of the System Identification course to my successor, Maarten Schoukens.

The opportunity to lecture is one of the prime reasons for choosing an academic career. I have taught courses in many different programs and at all different levels, from first-year BSc to MSc and PhD courses. And teaching has always been a great source of inspiration. Teaching is also the best way to get an understanding of a subject. That is why I always claimed to students that I learned as much from teaching a course as they did from following it. Over 40 years, the changes that have taken place in education have been drastic. From a time of no internet, with only books and sometimes lecture notes and personal notes taken while attending the lecture, to information being available any time, at any place, on any subject, including online video or YouTube recordings of the lectures (or lectures of other teachers in other programs worldwide). Alongside talking to the newer generations of students, the work of Alessandro Baricco [3] made me particularly aware of the fast changes that were taking place in the life and learning capabilities of our students. Up until my final courses, I kept my preference of using the chalk and blackboard to explain concepts and theoretical results. Conveying the message of a lecture while explaining the basic reasoning in the simplest terms has always been my particular challenge, leading to improvements in my story from year to year. However, its effectiveness relies on a concentration span of the student of at least 45 minutes, which has become a growing challenge for many. Among education specialists, the call for challenge-based learning (CBL) is now widespread. It is a very attractive model to activate students and to get them to the point of real problem-solving on the basis of self-acquired knowledge.

On the other hand, for me, it is not clear yet whether we have found convincing answers to two of what I see as the prime questions in university education:

(a) In the past, students would acquire analytical skills through the mastering of several theoretical subjects in the form of lectures and exams. Will CBL be an appropriate alternative for learning those skills?

(b) What are the exact skills that future engineers will need in view of the fact that massive amounts of information are available ubiquitously through Google, ChatGPT, etc.?

SUPERVISING STUDENTS

Figure 29. 44 PhD theses that I supervised.

The achievement of which I am most proud in my academic career is the success of the 44 PhD students who realized their PhD theses under my supervision. All of them individually went through a development process in which they grew towards independent researchers, mastering their topic and making substantial contributions. And all of them had their own challenges, pitfalls, hurdles, insecurities, blocks on the road, walls to be broken and time to manage and asked for different roles from a supervisor at different moments in time: stimulation, lifting energy, encouragement, critical questions, boosting self-confidence, backing off, helping out, tough discussions, etcetera. What I learned after all of these projects is that there is definitely no 'one size fits all' type of supervision and, even more so, that finding the right type of supervision in each individual case remains an important challenge in itself.

Final words and thanks!

At the start of my academic life, during my graduation project in the group of Pieter Eykhoff and supervised by Ad Damen and Andrzej Hajdasinski, the foundation was laid for a growing enthusiasm for research in the systems and control domain and, in particular, in system identification. Pieter Eykhoff's lectures and his 1974 book were a great inspiration and, with his international IFAC network, my eyes were opened to the international setting in which research takes place.

The strategic choice of Pieter Eykhoff and his group to connect to the Dutch systems theory and operations community through the national network MBST ('Mathematische Besliskunde en Systeemtheorie') gave us access to this community. As a young PhD student, I could attend the yearly Benelux Meeting and be inspired by people like Jan Willems, Huib Kwakernaak, Jan van Schuppen, Malo Hautus, Hans Schumacher and the upcoming younger generation of Henk Nijmeijer and Arjan van der Schaft.

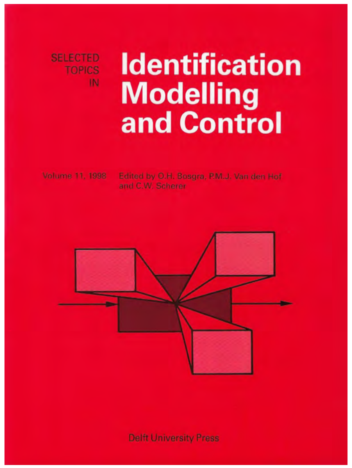
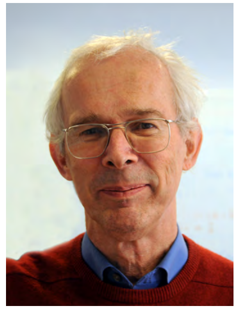


Figure 30. TUD group's periodical 'Selected Topics in Identification, Modelling and Control' (1990-2001).

The move to Okko Bosgra's group in Delft in 1986 and the step towards becoming an assistant professor in the Department of Mechanical Engineering there was a marking point. It was the start of a long-term cooperation with Okko, whose supervision, inspiration, support, ideas, wisdom, and striving for quality without compromise have definitely shaped my scientific values and attitude as an academic. The Mechanical Engineering Systems and Control group was a fabulous and inspiring working environment with many talented people. The results of the group's research became more and more visible internationally, also through the publication of the group's periodical 'Selected Topics in Identification, Modeling and Control' that was published and distributed among our (inter)national colleagues in the period 1990-2001.



Okko Bosgra

Jan Willems

Alongside Okko Bosgra's important role, Jan Willems, full professor in Groningen, was a great source of inspiration. Jan's driving force behind setting up a national PhD network in which graduate courses were taught, later leading to the establishment of DISC, was of paramount importance in the shaping and the resulting strength of the Dutch systems and control community. Besides that, his guiding role for young academics also helped me to team up with that community and to sharpen my mind on my academic positioning. Jan involved me in international workshops of his group and I regularly traveled to Groningen for individual research discussions and for pizza at Jan's place after a Systems Theory Day organized in Groningen. It would have been great to be able to discuss the developments of the last decade with him and he would definitely have been enthusiastic to see that with our dynamic network modeling, we made a strong move towards his behavioral view on dynamic systems and system interconnections. Both Okko and Jan are dearly missed.

The informal yearly micro-symposium, initiated in 2001 by Johan Schoukens in Brussels, brought together a small group of leading people in system identification and was the perfect place for informal discussions on new trends and contributions in the field in a very much open and informal atmosphere. In the period 2016-2019, we had the honor of hosting it in Eindhoven. I am indebted to the participants Johan Schoukens, Rik Pintelon, Lennart Ljung, Bart De Moor, Michel Gevers and, at a later stage, Håkan Hjalmarsson, Marco Campi and Alessandro Chiuso for their participation and support, stimulating debates and friendship.

Many international colleagues and collaborators have formed a worldwide network in which it was very stimulating and rewarding to interact. In particular, I would like to mention Graham Goodwin, who hosted my first international research sabbatical in Newcastle, Australia, back in 1992. I would also like to mention all partners from industries and institutes that participated in collaborative projects.

The departmental and university boards, first in Delft and later in Eindhoven, are acknowledged for providing the opportunities to develop both my own academic career and the university department and groups that I have been involved in. I have highly appreciated the climate of open debate and joint responsibilities. Thanks to Ton Backx for persuading me to make the move from Delft to Eindhoven.

My national colleagues in DISC are acknowledged for shaping and maintaining a great community that we can still be very much proud of.

I am indebted to many colleagues in TU Eindhoven for teaming up in joint endeavors, including Impulse, HTSC, EAISI and AI&ES, to my colleagues at ME and EE for maintaining a great MSc program in Systems and Control and, in particular, to my colleagues in the Department of EE for shaping a friendly environment for collaborative partnership and joint ownership of the department.

In building and extending the CS team, we have been able to shape a group of highly talented people in which individual development and group performance and responsibilities are very well-balanced in a climate of open debate and mutual respect. I am very proud of the internal lines of cooperation that we have been able to establish. It has been extremely rewarding to be part of this group development. Thanks a lot: Siep, Mircea, Roland, Leyla, Tijs, Sofie, Maarten, Zhiyong, Amritam, Valentina, Will, Wim, Hiltje and Diana.

During the time of the COVID lockdown, I made the decision to step down from my managerial responsibilities on my 65th birthday in 2022. I am very thankful to Siep Weiland for taking over my role and for further guiding the CS group into the future. I have full confidence that CS will continue to flourish with all of the scientific and technological challenges that are on the table.

For the great operational support that I received during the last 12 years, I am very grateful to Barbara, Diana and Hiltje. Besides providing excellent professional support, they managed to maintain a cheerful nerve center in our group's secretarial office.

And last but not least, I am indebted to all BSc, MSc and PhD students who took my courses, provided feedback and raised questions that helped me improve my understanding and the quality of my lectures. And to all students who participated in our research and made important contributions to the development of our systems and control field: thank you!

For raising me to the person that I became and for having always supported me, I owe a lot to my parents, who unfortunately are not with us anymore.

En dan kom ik bij de kleinste circkel, ons gezin, Irma, Malon en Cas, later uitgebreid met Niels, Tessa, bonus-kleinzoon Max en onze twee kleindochters Valérie en Emy. Dank voor het warme en hechte thuisfront met betrokkenheid en aandacht voor ieders pad in het leven. Irma, we zijn op een fantastische levensreis gegaan samen. Dank voor alle eindeloze steun en liefde; ik hoop dat we nog lang van onze gezamenlijke reis mogen genieten.

Ik heb gezegd.

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Curriculum Vitae

Prof.dr.ir. Paul Van den Hof was appointed as a full professor of Modeling and Control of Dynamical Systems in Electrical Engineering in the Department of Electrical Engineering at Eindhoven University of Technology on September 1, 2011.

Paul Van den Hof (Maastricht, 1957) received his MSc degree (1982) and PhD degree (1989), both in Electrical Engineering, from Eindhoven University of Technology. He was affiliated with Delft University of Technology from 1986 to 2011, where he was appointed as a full professor of Model-Based Measurement and Control in 1999. In 2004, he became founding co-director of the Delft Center for Systems and Control, a merger of three systems and control groups from three different departments in TU Delft. In that capacity, he led the introduction of the MSc program in Systems and Control. In the period 2005-2014, he served as scientific director of the Dutch Institute of Systems and Control (DISC). He led the Control Systems group in the Department of Electrical Engineering of TU/e from 2012 to 2022 and was among the initiators of the Eindhoven Artificial Intelligence Systems Institute (EAISI) in 2019 and the related MSc program Artificial Intelligence & Engineering Systems. He has had several positions in the International Federation of Automatic Control (IFAC), including the position of Vice-President in the triennium 2017-2020. He is a holder of an ERC Advanced Research Grant (2016) and an ERC Proof-of-Concept Grant (2023). Paul is a Fellow of IFAC, Life Fellow of IEEE, IFAC Advisor and Honorary Member of the Hungarian Academy of Sciences.

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