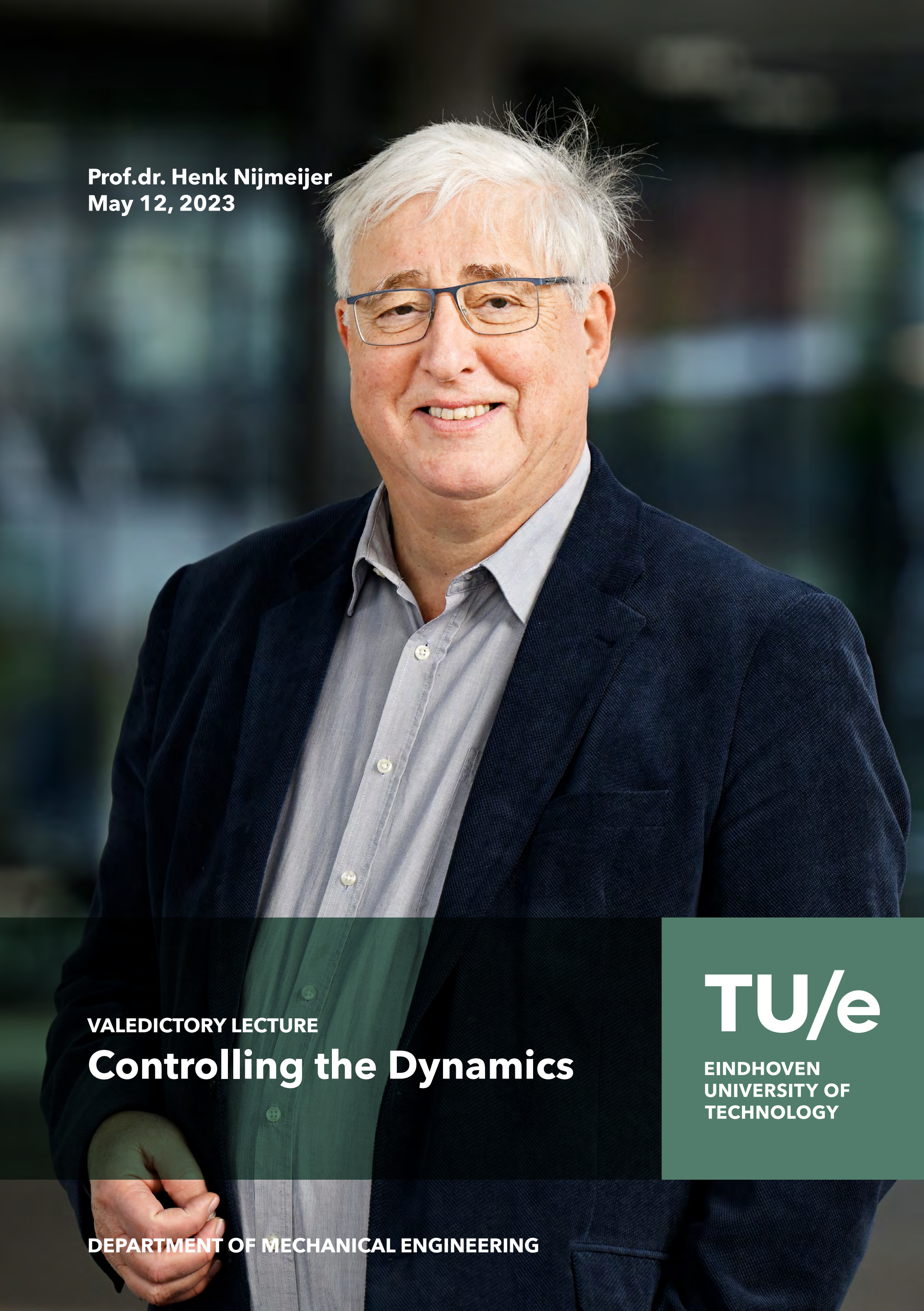
Controlling the dynamics



Prof.dr. Henk Nijmeijer
May 12, 2023

VALEDICTORY LECTURE

Controlling the Dynamics

EINDHOVEN UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF MECHANICAL ENGINEERING

VALEDICTORY LECTURE PROF.DR. HENK NIJMEIJER

Controlling the Dynamics

Presented on May 12, 2023
at Eindhoven University of Technology

Introduction

Geachte Rector, leden van het College van Bestuur, beste collega’s, beste vrienden en toehoorders, lieve familie. Het is me een groot genoegen om dit college vandaag te geven dat ik omwille van het gehoor grotendeels in het Engels zal geven.

I once learned that the main points in a valedictory lecture are the acknowledgements and the drinks afterwards at the reception. I therefore strongly hope you can wait a little before I let you go.

In December 1979, I finished my Mathematics degree at the University of Groningen and thereafter I have always worked in academia. I also defended my PhD thesis in Groningen - again in Mathematics - though was at that time affiliated with the CWI in Amsterdam. More precisely, by the defense date I had already moved to the University of Twente, where I worked until 2000 and whereafter I moved here to Eindhoven. This was, all in all, a fairly long period and I rapidly concluded that the time today is simply too short to focus attention to all of what I consider relevant over that period, so I will only present a few snapshots of what I have done and, more relevantly, the messages that I wish to convey to you today.

Controlling the Dynamics

The title of today's lecture is inspired by my inaugural lecture [1], which reads in Dutch as 'Dynamisch Geregeld' and which paraphrases the group's name - Dynamics and Control - that I chose upon accepting my full professorship in Eindhoven after a short three-year intermezzo as a part-time professor of Nonlinear Control in Mechanical Systems. It was always my plan to take 'Geregeld Dynamisch' as the title for this farewell lecture, but this did not work well as nowadays a valedictory lecture is assumed to be in English. At the same time, the Dutch title expresses something quite important to me, namely the emphasis on changes in my research interests throughout my career at the university. I have taken a long journey from pure mathematics to mechanical engineering, from theory to applied research, from individualist to cooperator, from mono-disciplinarist to multi-disciplinarist, and certainly more. 'Controlling the Dynamics' also stands for the needed and very much desired changes in my (research) activities over the past more than 40 years in academia. And to add to this, I also plan to remain 'Geregeld Dynamisch' after today's farewell lecture.

Nonlinear Control

In [1], I already introduced 'nonlinear control' as one of the pillars of my research, and it was for this expertise that the late TU/e Mechanical Engineering professors Jan Kok and Dick van Campen invited me to join the Department of Mechanical Engineering as a part-time professor in 1997. My experience at that time was mostly on the theoretical side with a few exceptions towards robotics, as is also evident from the book 'Nonlinear Dynamical Control Systems' [2] that I wrote with my colleague Arjan van der Schaft and which can be viewed as a partial outgrow of my PhD thesis. Indeed, within the mechanical domain, almost all systems are nonlinear and only a very limited class of mechanical systems can be adequately and accurately modeled as a linear system. There are numerous reasons for this, such as geometric nonlinearities, friction, contact, play and, finally, (spatial) constraints. As I discussed in [1], the actual application of all of the beauty of the book [2] turned out to be highly nontrivial, particularly due to the aforementioned typical nonlinearities that are often extremely difficult to model/identify in a sufficiently precise manner. Nevertheless, in retrospect, I can say that we have been able to address the modeling-identification-control paradigm in numerous cases, which is evident from several PhD theses and a large number of journal publications. Some of the examples have been investigated in close collaboration with industrial partners, which has certainly shaped my thinking as an engineer and hopefully has done so for my industrial colleagues. In addition, when I started here in Eindhoven, the DCT lab was still a new environment for me (DCT stands for 'Dynamics and Control Technology', which indicated the joint nature of the lab of the Dynamics and Control group and the Control Systems Technology group; in the meantime, the name has been changed a few times). Despite the intrinsic nonlinear systems encountered in practice, like mobile robots, rigid robot manipulators or drill string pipe dynamics, many industrial control problems are still of a linear nature, possibly corrupted by noise-like disturbances. Much in-depth engineering labor goes into the modeling and identification of such disturbances.

However, in the last few years, a completely new turn towards nonlinear and hybrid control has been made with the paper [3] (see also [4]), perhaps the first marker of this new line. While a substantial class of problems for nonlinear control systems aims at (feedback) linearizing a nonlinear system and then applying standard linear control methods, the recent work changes this perspective drastically and exploits nonlinear controllers for a linear control system, thereby enabling performance requisites that are impossible when remaining in the domain of linear control. For this purpose, Hybrid Integrator Gain Systems (HIGS) are used in closed-loop control, which, among others, can lead to suppressed overshoot effects in non-minimum-phase systems. It has been a great experience to see the potential of the work emerging from [3] and it is a real pleasure to acknowledge the excellent collaboration with the authors of [3, 4]. A key feature of such a HIGS element in a control loop is visible in the diagram of figure 1 which nicely demonstrates the essential part of HIGS, as can be seen how the typical integrator overshoot has been considerably suppressed by the timely switching of the integrator action upon a sign change between the error and input signal. Although ideas on using nonlinear control in linear systems are not totally new, I am convinced that the use of HIGS in the control loop will find broader application in industrial motion systems.

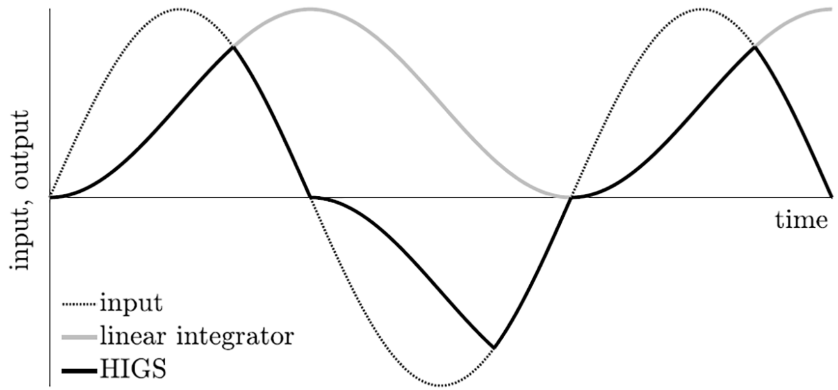


Figure 1. Time response of a HIGS block versus input and linear integrator, cf. [3, 4].

Synchronization and Cooperation

In 1996, I was on a sabbatical in Canberra, Australia, after a four-year term as vice-dean of Applied Mathematics at the University of Twente. This sabbatical was quite instrumental in shaping some of my future research lines, including synchronization or coordination. The interest in this was partly caused by the fact that I was invited to be a lecturer at a summer school on Chaos Control and Synchronization for physicists and dynamics people in Italy, and although I was well-acquainted with control and chaos by then, synchronization was fairly new to me. Synchronization has a very intuitive meaning in that certain processes, animal behaviors or machines exhibit some identical or similar behaviors – here, 'similar' can also refer to phase-shifted identical dynamics. Obvious examples in nature are, for instance, a school of fish or birds flying in a V-shape formation. With a bit of further study, it becomes clear that even our human bodies and brains are full of synchronized dynamics. But simple mechanical examples also exist, like pendulum clocks swinging in anti-phase or organ pipes that feature sound and anti-sound, as formulated by Lord Rayleigh in 1877.

I would like to show some of the work on synchronization that I have been involved in over the past years.

Before going into some of the more engineering-oriented examples, I first want to emphasize one of the main challenges that arises in the study of synchronization, namely: what causes the joint motion? This question is simple to ask but turns out to be extremely difficult to answer for various cases in nature. As a simple example, I like to mention the synchronized calling behavior of Japanese treefrogs [5] or the synchronized combustion of a pair of candles [6].

An interesting example of – controlled! – cooperative motion in robots was the subject of the PhD thesis of Alejandro Rodriguez, published in an adapted form in [7], where we see how the motion of two rigid robot platforms are fully synchronized by means of smart controller design and, despite disturbances, the robots manage to keep their joint motion, thereby allowing only a slight degradation of the tracking performance. One could say that the robots exhibit social behavior in executing the desired tracking task, and this is fully achieved through a clever trade-off between the coupled motion of the robots and the trajectory tracking. Following the work of Rodriguez, the research on cooperative motion and synchronization has taken several routes. On the one hand, the PhD thesis of Jeroen Ploeg – in collaboration with TNO – was a landmark on Cooperative Adaptive Cruise Control (CACC), which is an extension of Adaptive Cruise Control and makes platooning at short(er) intervehicle distances possible thanks to wireless communication between the vehicles; see [8]. The wireless communication velocity of a preceding vehicle is directly used as a (desired) velocity feedforward for the following vehicle. To show the feasibility of the fundamental results from the thesis, the full PhD committee, including the Rector Magnificus, were – safely – CACC-driven from TU/e to the castle in Helmond, where the public defense took place.

The first mention of synchronization, or rather when the term 'sympathy' was coined, was by the Dutch scientist Christiaan Huygens (1629-1695), who described in his notebook an intriguing experiment that had its roots in the question of how sailors can locate themselves while sailing the sea; see [9].

Figure 2. PhD defense of Jeroen Ploeg at the Helmond castle with a CACC equipped vehicle.

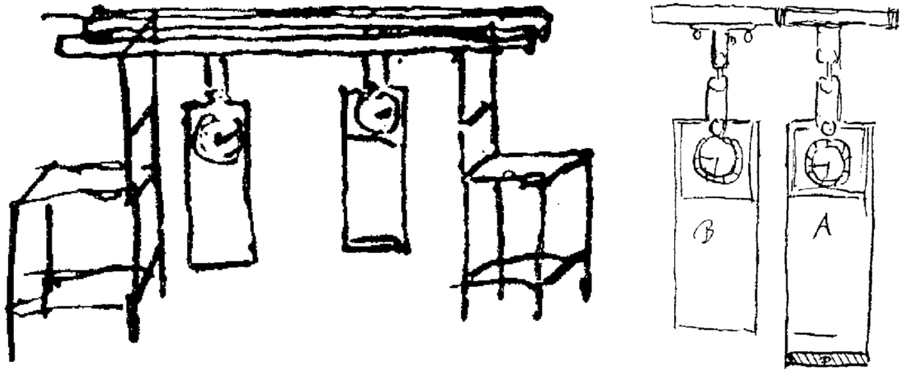


Figure 3. Drawing of 'sympathy' of pendulum clocks, from Huygens' notebook 1665, [9].

In a letter to his father, Constantijn Huygens, he wrote (in Latin!): "…hence, [when] the clockworks were at a small distance separation I began to suspect a certain **sympathy**, as if one were affected by the other …". Christiaan Huygens indeed asked himself where the (anti-)phase synchrony of the pendulum clocks comes from and he realized that the connecting beam forms the medium for this. This insightful observation was made at a time when differential calculus was still to come (Newton!) and thus a notion of energy transfer was still far away. On the other hand, even today, despite advanced numerical modeling abilities, a full understanding of the synchronization of connected oscillators is still lacking. And although I feel like Christiaan Huygens' 'grand-grand-… son', there are still more questions than answers regarding collective motion. Together with Jonatan Pena Ramirez, a former PhD student and nowadays a collaborator, I have extensively worked on clock synchronization (see [10, 11, 12]) and I would like to showcase one specific example of the work here – the word 'showcase' is fully justified as the experiment below is displayed in a museum in Mexico!

In collaboration with the clock factory *Relojes Centenario*, located in Zacatlan, Puebla, Mexico, multiple clocks were designed and constructed ad hoc to be *as identical as possible*. We then placed two of these monumental clocks on a wooden table; see figure 4, which is a photo taken at the museum of *Relojes Centenario*.

Figure 4. Huygens' set-up in *Relojes Centenario* museum, Zacatlan, Puebla, Mexico.

The pendula of the clocks are initialized in opposite positions. However, after transient behavior lasting approximately 30 minutes, the pendula reach consonance such that the pendula oscillate in the same direction and at the same frequency and amplitude, i.e., the pendula of the clocks are synchronized in-phase.

Once the clocks are synchronized, they remain in this state as long as there is potential energy stored in the weights driving the escapement mechanism.

The experiment and the subsequent analysis of it have led to a few interesting conclusions, one of which I will describe here. In taking two identical clocks for the synchronization experiment, the idea of Huygens was that the two synchronized clocks would run at the same frequency as the individual and isolated clocks, but, as the next figure, figure 5, shows, the synchronized clocks have a noticeably lower frequency, making them rather poor timekeepers; during a full 24-hour day, the difference is close to 20 minutes!

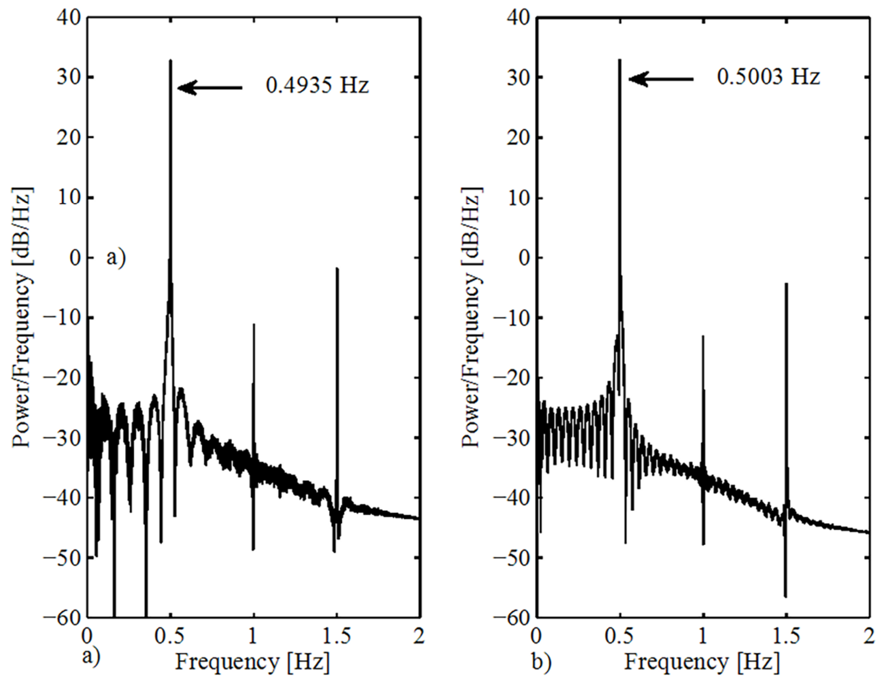


Figure 5. Frequencies of coupled (left) and uncoupled (right) clock, cf. [10, 11, 12].

Our work on this topic attracted much attention, particularly as the underlying analysis revealed the exact cause of the slower rhythm, as well as when the clocks will swing in-phase or anti-phase, which is another noteworthy conclusion of our research. Does this sort of complete this research? Not at all, in fact, it raises numerous related problems all centered on synchronized motion between oscillators. To illustrate this, one should simply think about a situation in which more than two clock pendula are placed on a (flexible) platform. In that situation, the clocks may exhibit various synchronized modes depending on the specific geometry of how they are placed on the platform, including in-phase and anti-phase synchrony but also, depending on the initialization of the pendula, other types of common motion. With a few metronomes, one can even rapidly encounter various interesting behaviors; see e.g., [13, 14], [15, 16].

Synchronization is certainly not limited to oscillatory systems but is noticeable in numerous other types of systems. At a first glance, perhaps the most astonishing case is the synchronization of two identical chaotic systems! On the other hand, this is not too surprising given the close resemblance between the synchronization of two coupled systems and the error dynamics of an observer in a control system; cf. [17].

Complexity and Emergent Behavior

The synchronization of multiple – identical - systems is a particular form of collaborative motion that may arise in a network of coupled systems. In general, it is still largely unclear how to analyze such networks and what factors are crucial in this. As mentioned by Huygens, the coupling is one essential part here, but the coupling itself can also have different forms like static or dynamic. I have become very interested in these exciting questions, often referred to as 'complexity', and this forms one of my connections to the Institute for Complex Molecular Systems (ICMS) at TU/e. Key elements in complexity are, at the very least, the network and its connections and the underlying individual oscillator dynamics. Possible emergent behavior provides structure in the joint motion between the individual oscillators, like the in-phase synchronization of two Huygens' clocks.

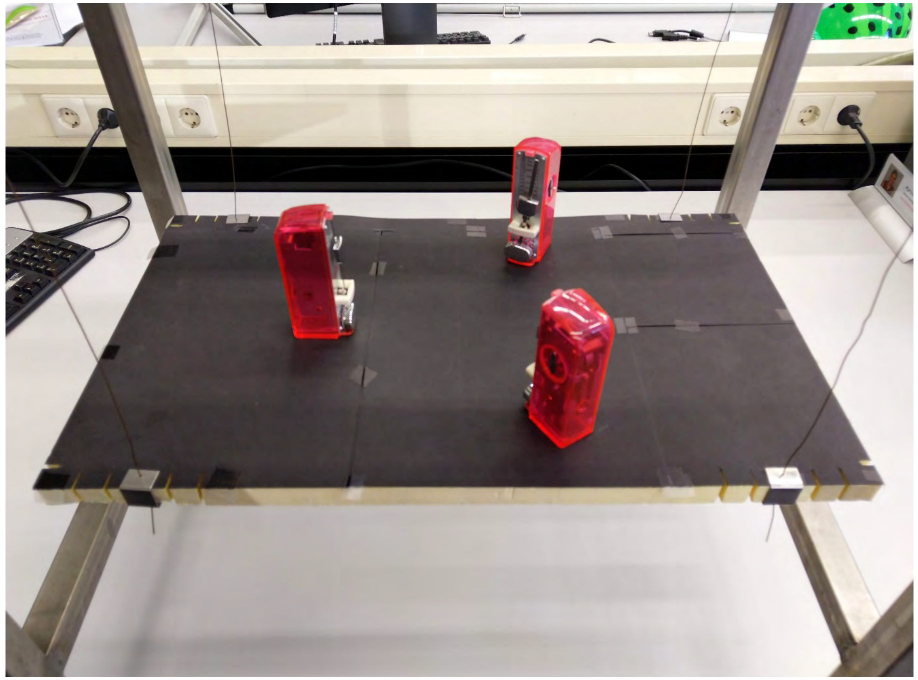


Figure 6. Three metronomes on a freely moving platform, cf. [16].

Emergent behavior is very common in nature and biology; as an example, one can think of birds flying in a V-shape that lose the characteristic formation if an additional bird wants to join. The synchronized calling of Japanese treefrogs is another illustration of this phenomenon. Complexity research is still in its infancy and great questions lie ahead in this field, especially as we see it everywhere in nature and biology but also in engineering systems. In this context, I will only mention traffic behavior resulting from cooperative (connected) vehicles or a windmill farm, where the primary goal of maintaining a stable power grid is one of the challenges in global energy systems.

A totally different view on questions of emergent behavior can be seen in numerical solution procedures of advanced ordinary and partial differential equations, where the typical spatial gridding in combination with the time-stepping procedure determines how the solution of the partial differential equation is computed. But how fine must the gridding be and what is an acceptable, sufficiently small time step in such a procedure? Here, all of the ingredients for multiple oscillators/systems, as discussed above, arise but now with the requirement that the numerical solution provide an accurate solution to the original differential equation. This subject has so far received limited attention in synchronization literature.

Automotive Technology

After a few years in Eindhoven (it must have been around 2002), we – that is to say, the Mechanical Engineering professors – initiated a plan to set up an automotive track within the Mechanical Engineering master's curriculum. At the meeting, I rather innocently claimed the vehicle dynamics part of the educational program. At that time, I certainly did not foresee where this would lead, particularly as my expertise in vehicle dynamics was very limited and specific expertise was surely required to establish a good basis for automotive engineering. Without going into details, the initiative from 2002 has led, with strong momentum from my Control Systems Technology colleague professor Maarten Steinbuch, to a complete Automotive Technology (AT) educational program with a bachelor's track, master's program and EngD program. This AT curriculum is truly interesting, with participating staff in the educational program coming not only from Mechanical Engineering but also from Computer Science, Electrical Engineering, Industrial Design and others, making it a true multi-disciplinary program. The decision to build an AT program rooted in the different disciplines came from the fact that nowadays a car is full of inputs from these disciplines, as many of you will recognize when driving a car. I still regret that no Smart Mobility Center has been formed at TU/e alongside this full-grown AT education program, as TU/e has reached a unique position in this domain – unique not only in the Netherlands, but also far beyond! As an aside, we have seen a very similar integration of elements from electrical and mechanical engineering with software engineering in high-tech systems over the last decade(s), perhaps hinting at what a high-tech engineer of the future may need.

I would like to explain some of the automotive activities we undertook in the Dynamics and Control group in the past decade, especially as I believe that it forms an excellent illustration of what is required for modern high-tech systems. To do so, I want to introduce the NWO Perspective Program Integrated Cooperative and Automated Vehicles (i-CAVE), of which I acted as program leader. The program, with a budget of more than € 4.5 million, started in 2016 and consisted of seven projects and more than 20 young researchers overall; see [17].

As the name suggests, i-CAVE dealt with automated vehicles – which are not necessarily the same as autonomous vehicles! – and a summary of the program, drafted in 2015, is given below:

"This research programme addresses current transportation challenges regarding throughput and safety with an integrated approach to automated and cooperative driving. In i-CAVE a Cooperative Dual Mode Automated Transport (C-DMAT) system is researched and designed, consisting of dual mode vehicles which can be driven automatically and manually to allow maximum flexibility. The programme integrates technological roadmaps for automated and cooperative driving, accelerating the development of novel transportation systems addressing today's and future mobility demands. Besides these enabling technologies, focus is put on fault tolerance and fail safety, wireless communications, human factors, and others addressing transition of control between manual and automated driving and response of other road users. i-CAVE tackles the main challenges of automated driving, i.e., achieving high levels of safety and reliability through rigorous technological design, combined with seamless integration between automated and manual driving to obtain maximum flexibility and user acceptance. A living-lab will be used for the integration and evaluation of accurate vision-based mapping and localization techniques, distributed cooperative vehicle control algorithms and fleet management methods. In addition, it allows for a close-to-market transport system, which can be commercialized by the transport industry, specifically leading automotive tiers in the Netherlands, by applying the results in their roadmaps."

Of course, the ambitions of the program and the separate research projects have perhaps not all met expectations and the living lab work was certainly seriously hindered by the past COVID-19 years. On the other hand, a testimony of the successes of the program can be found in a book nicely entitled 'The Future of Moving Forward'; see [17] and figure 7.

I will discuss one of the specific projects here as it shows some of the greater challenges in high-tech automation. In the i-CAVE program, an automated vehicle was created from a Renault Twizy; in this context, the term 'automated' refers to adding a steer and brake actuator to the donor vehicle. With these added electronic systems and by further adding adequate sensors on board, the challenge is to 'close the loop' to make the vehicle able to autonomously follow a prescribed trajectory without collisions. Various facets of this simple-looking task have been developed by different young researchers with backgrounds in one of the AT departments.

Figure 7. i-CAVE: The Future of Moving Forward, cf. [17].

Figure 8. One of the automated i-CAVE vehicles, cf. [17].

One of the projects focused on the problem of creating automated merging in a platoon strategy; see [18]. Anyone familiar with highway driving will have experienced how difficult it is to merge into a densely populated highway lane, which in fact somehow requires willingness from other drivers to successfully complete the merging. Such social behavior is exactly what is also needed in the project on vehicle merging into a platoon as the automated vehicles that drive in a platoon use cooperative adaptive cruise control, which make the platoon vehicles drive at a close optimal intervehicle distance. To allow merging, some of the platoon vehicles must therefore create additional spacing, which is exactly the social behavior described earlier for human drivers; see [18] for a schematic illustration and further discussion on the required controller. The problem discussed here is representative of numerous automation problems in which there is a requirement for either interaction between autonomous vehicles or, one step further, interaction (or cooperation) with humans. Mathematically, this may call for a game-theoretic approach but, so far, experience in both theory and experiments in this direction is quite limited.

Soft Robotics and Human Interaction

In 2018, together with colleagues from the University of Twente, Wageningen University and Delft University of Technology, I was involved in establishing the 4TU Soft Robotics program; see [19]. A nice illustration of a 3D-printed soft robot developed by Brandon Caasenbrood, cf. [20], can be seen in figure 9.

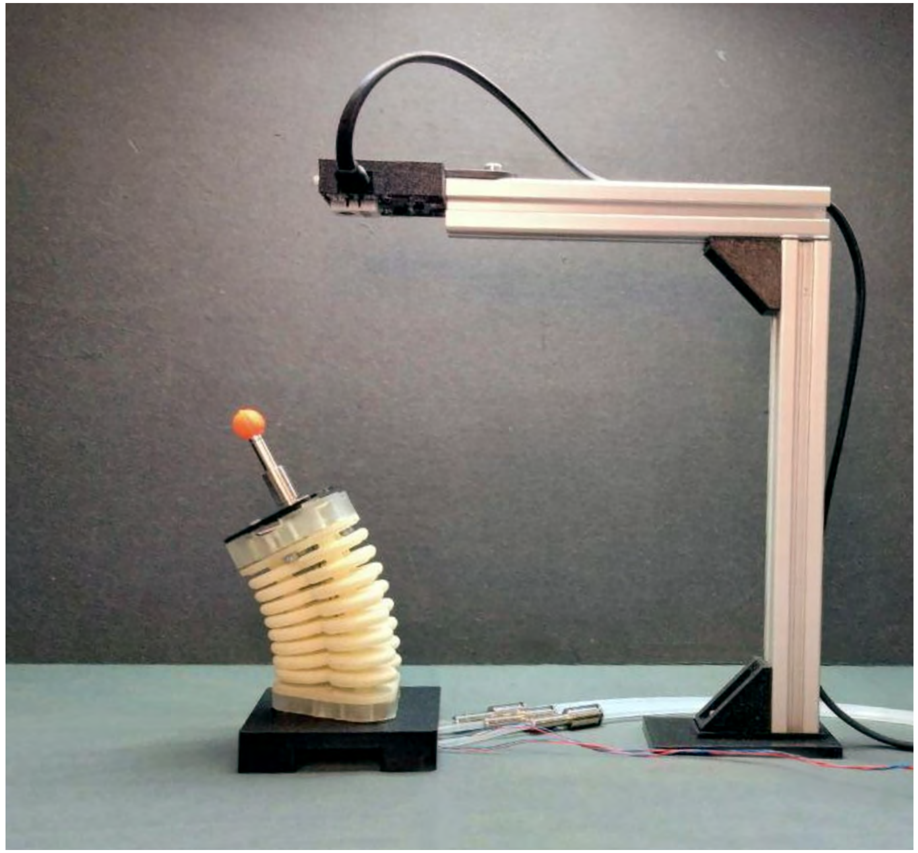


Figure 9. A simple 3D printed soft robot, cf. [20].

With the rapid growth of automation and autonomous systems, there are two important aspects that deserve attention, namely interaction and cooperation with humans. This hints towards two points at least. First, at the technical level, human interaction with robots/machines always brings in the danger of inadvertent contact or collision between human and robot. This is one reason to have soft robots, i.e., robots that exhibit large flexibility in regard to their surroundings and thus in regard to wanted or unwanted contact. Another argument in favor of a soft machine is its adaptability to its task or environment, thereby allowing a controlled change in the flexibility of the robot. Note that in the latter case, the intrinsic properties of the robot material are subject to change, and we also touch upon the field of soft materials, an extremely fashionable area now in the study of many fields, such as physics, material science and chemistry. This also illustrates the link between the soft robotics field and the ICMS, again demonstrating my link with the institute.

There is one further aspect of the human interaction with autonomous or automated robots, namely the human perception of automation in general and specifically the ways in which humans can interact with automated machines. Everyone has probably experienced how a new tool, like a mobile phone or iPad, requires some additional learning. But is today's smart vehicle not approaching a wheeled smart phone? And how to act/re-act if you, as a pedestrian crossing a road, see an automated vehicle approaching? Is it irrelevant whether the car is autonomous or human-driven? The latter example was studied in the i-CAVE PhD thesis of [21]. There are numerous other examples of this sort and I really believe that for this society, automation requires a much stronger base in technology and psychology. For this reason, more attention for psychology in technology is highly recommended.

The Dutch Institute of Systems and Control (DISC) and University Education

In the past half a century, the field of systems and control has become an important and very active research area in the Netherlands. Systems and control, often considered a hidden technology, is fundamental to an understanding of the (regulated) behavior of almost any system, be it engineering, physical or even economic. It has also become unavoidable in any automated engineering system and, for this reason, the teaching of systems and control has become a basic part of education at all technical universities in the Netherlands, as well as at some of the general Dutch universities. Historically, a boost in this development was given in the seventies and eighties by internationally trained staff, including Jan C. Willems, Huibert Kwakernaak, Ruth Curtain, Malo Hautus and others. Besides the local curriculum, they also cared about a nationwide PhD program that enabled young researchers to attend weekly advanced and specialized courses in systems and control at a central location in Utrecht, making such education efficient and accessible for both teachers and students. The above developments were formalized in the Dutch Network for Systems and Control in 1987, subsequently the Dutch Institute of Systems and Control (DISC) from 1995 onwards. A nice account on the formation of DISC with its broader impact can be found in [22]. Notably, when the status was raised to a national research school, the role of coordinating university (in Dutch: 'penvoerder') and scientific director became a true point for discussion in university politics. It was decided that Delft University of Technology would act as the coordinating university, with professor Huibert Kwakernaak as the first scientific director of DISC. The accreditation of DISC as a research school by the KNAW in the period 1995-2016 has been valuable for the field in many ways. It served as a marker for quality – and this still applies! – but also contributed to the visibility of the systems and control field. DISC also served as a vehicle for establishing and supporting novel research initiatives by NWO and the technical universities through a large €10 million grant for the 2005 High Tech Systems Center program [23] of the Ministry of Education and Research.

I have been involved from its earliest existence as the Dutch Network on Systems and Control and thereafter DISC and, since 2014, I have acted as the scientific director of the DISC. Even though the KNAW accreditation no longer exists, DISC still acts as an education platform with, among other things, PhD courses and summer and winter schools on systems and control, of which the credits are acknowledged by all participating universities. I am very pleased to mention this as it demonstrates how well we, as a community, have been able to continue our activities despite substantial changes in university policy and education.

On the other hand, there are serious threats in what we teach our PhDs. Clearly, all courses are taught by our experts in systems and control, but I must confess that novel developments in machine learning and artificial intelligence can be useful in future controller design. The question of how to integrate this in future control courses by our young researchers may become one of the greater challenges as this is already becoming visible at the bachelor's and master's levels. At the same time, an artificial (intelligent) controller, as smart as it might be, is hard – or impossible in many circumstances – to understand for any control specialist and consequently the control performance and fault security may soon become debatable. The further development and understanding of what is called a 'digital twin' will become more and more important and will help to link modeling outcomes to real engineering systems. Research on digital twins is now widely adopted in the Dynamics and Control group as well as at many other departments.

University education has always been subject to direct influences from research and societal developments. Such changes have become more and more visible in the last decades and this would not have been the case without the important roles that the computer and the internet are playing in everyday life. Numerical algorithms have become faster and more reliable and much more relevant information may now be obtained from the internet. I even considered including a paragraph written by ChatGTP in this valedictory text, assuming it would likely go unnoticed! The changes we all experience around us are also appearing at an almost exponential speed. Likewise, knowledge, as measured in terms of written texts, is growing exponentially, making it almost impossible for a researcher to follow everything which is relevant, even in her/his own specialism. To illustrate this further, I receive requests almost daily from newly established journals to join the editorial board or to provide a scientific contribution with a guaranteed journal publication within a few months at most, but at a certain price! Publishing has become not only part of a scientist's life but also a business model for many others. It is not easy to extract an answer to the above threats in terms of both the individual student and researcher nor in terms of science development. I will not try to provide simple advice on how to cope with this knowledge growth, but I think at least that everyone, including university policymakers, should be fully aware of it and, in many cases, also be alert regarding the enormous impact that it may have. This will also include teaching where all the effects that AI -and internet! - may have, are still beyond our horizon.

Epilogue and Thank You

During my career at the university, I have been fortunate to work with many people, ranging from students, PhDs and postdocs to scientists and technical and administrative staff. I made a quick check of how many collaborators I may have worked with over the years by simply counting the number of co-authors. Using Scopus, the outcome was 159 co-authors based on a set of 713 counted conference and journal papers, but Scopus allowed for a maximum of 160 co-authors (including myself). Therefore, my apologies to all co-authors not included in these numbers! Not included in this list of co-authors are all others at the university that have helped me equally well.

I am extremely thankful for all the collaborations I have had and I believe that I would not stand here without all of their help. When I started my Dynamics and Control group in 2000, this was a new avenue within the Department of Mechanical Engineering. It has been a great adventure to collectively build this into a large and very active group that will also continue under the same name after my retirement. In this context, I also want to thank all supporting staff and especially my secretarial support at D&C and DISC: Lia, Geertje, Martha and Renate, thank you so much!

I would like to thank the university and the Department of Mechanical Engineering for creating the opportunities to work in a stimulating and inspiring environment. I have truly enjoyed the interactions I have had with so many people here, as well as outside of TU/e. This includes my fellow researchers outside of Eindhoven in the Netherlands and beyond, but also the many international collaborations I have been able to build. For sure, these will not end today!

The risk of writing an acknowledgement at the end is to forget someone. I truly hope not to offend anyone by keeping myself to a very limited group of people. At the University of Groningen, I studied and graduated in Mathematics under the late professor Floris Takens, who geared my love for nonlinear dynamics and who taught me what mathematical rigor means. In this lecture, I also want to acknowledge my PhD thesis advisor, professor Jan Willems, who regrettably passed away in 2013 and who raised my interest in the systems and control field. My first steps in the control arena were partly made with Jan and my colleague

Arjan van der Schaft, with whom I wrote our classic research monograph [2] in the late eighties that marked the start of our nonlinear control profile.

Ik wil afsluiten met de mensen die ik eigenlijk als eerste zou moeten danken. Dat zijn mijn ouders, die me altijd hebben gestimuleerd om verder te gaan leren. Dat is tot de dag van vandaag gelukt, zoals ik hopelijk hier heb kunnen laten zien. Jammer dat ze er niet meer bij zijn. Uiteraard wil ik mijn vrouw Marjolijn en dochter Lianne bedanken. Bij mijn intreerede heb ik jullie de echte dynamica genoemd. Dat klopt nog steeds, en past nog steeds goed bij de titel van deze afscheidsrede. Dankjewel daarvoor!

References

1. H. Nijmeijer, Dynamisch Geregeld, Intreerede, Eindhoven University of Technology, 2003.
2. H. Nijmeijer, A. J. van der Schaft, Nonlinear Dynamical Control Systems, Springer, 1990, 3rd printing, 2015.
3. D.A. Deenen, M.F. Heertjes, W.P.M.H. Heemels, H. Nijmeijer, Hybrid integrator design for enhanced tracking in motion control, Proc. ACC, pp. 2863-2868, 2017.
4. D.A. Deenen, B. Sharif, S. van den Eijnden, H. Nijmeijer, M. Heemels, M. Heertjes, Projection-based integrators for improved motion control: formalization, well-posedness and stability of hybrid integrator-gain systems, Automatica vol 133, 109830, 2021.
5. I. Aihara, Modeling synchronized calling behavior of Japanese treefrogs, Japanese tree frogs, Physcal Review E, vol 80, 011918, 2009.
6. Hiroyuki Kitahata, Junji Taguchi, Masaharu Nagayama, Tatsunari Sakurai, Yumihiko Ikura, Atsushi Osa, Yutaka Sumino, Masanobu Tanaka, Etsuro Yokoyama, Hidetoshi Miike, Oscillations and Synchronization in the Combustion of Candles, Jnl of Physical Chemistry A, vol. 113, 8164-8168, 2009
7. H. Nijmeijer and A. Rodriguez, Synchronization of Mechanical Systems, World Scientific, London 2003.
8. J. Ploeg, Analysis and Design of Controllers for Cooperative and Automated Driving, PhD Thesis, Eindhoven University of Technology, 2014.
9. Huygens, C. Correspondence 1664–1665. In Nijhoff, M. (ed.) *Oeuvres complètes de Christiaan Huygens* vol. V (La Societe Hollandaise des Sciences, The Hague, 1893).
10. J. Pena Ramirez and H. Nijmeijer, The secret of the synchronized pendulums, Physics World, pp.36-40, January 2020.
11. H. Nijmeijer and J. Pena Ramirez, De sympathie van twee slingeruurwerken, wat zag Huygens niet? Tijdschrift voor Natuurkunde, pp.36-39, February 2017.
12. J. Pena Ramirez, L.A. Olivera, H. Nijmeijer and J. Alvarez, The sympathy of two pendulum clokcks: beyond Huygens' observations, Scientific Reports, March 2016.
13. Tohru Ikeguchi and Yutaka Shimada, "Analysis of Synchronization of Mechanical Metronomes,", in V. In, P. Longhini and A. Palacios (eds), Proceedings of the 5th International Conference on Applications in Nonlinear Dynamics. Understanding Complex Systems. Springer, Cham, pp. 141-152, 2019.
14. Ikeguchi Laboratory (Saitama University). https://www.youtube.com/user/IkeguchiLab.
15. Hoogeboom, F.N., Pogromsky, A.Y. & Nijmeijer, H. Huygens' inspired multi-pendulum setups: Experiments and stability analysis. Chaos: An Interdiscip. J. Nonlinear Sci. 26, 116304, DOI: 10.1063/1.4965031 (2016)
16. R. Hoogesteeger, A.Yu. Pogromsky, H. Nijmeijer, Emergent patterns in systems of planarly coupled pendula: Huygens' synchronization in two dimensions, preprint, 2022.
17. H. Nijmeijer, T. van der Sande, J. van der Sar, The Future of Looking Forward, 2021
18. W. Scholte, P.W.A. Zegelaar, H. Nijmeijer, A control strategy for merging a single vehicle into a platoon at highway on-ramps, Transportation Research Part C: Emerging Technologies, 136, 2022.
19. https://www.4tu.nl/soft-robotics/
20. B. Caasenbrood, Design, Modelling and Control strategies for soft robots, PhD thesis (to appear), Eindhoven University of Technology, 2023.
21. Dey, D., External communication for self-driving cars: designing for encounters between automated vehicles and pedestrians. PhDThesis Eindhoven University of technology, 2020.
22. J.J. de Boer, DISC in control, a history of the Dutch Institute of Systems and Control 1987-2012, DISC, 2012

Curriculum Vitae

Prof.dr. Henk Nijmeijer was appointed as a full professor of Dynamics and Control in the Department of Mechanical Engineering at Eindhoven University of Technology (TU/e) on May 1, 2000.

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