MSC THESIS PROJECTS
IN SYSTEMS AND CONTROL
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Numerics for Control and Identification (NCI)

- prof.dr.ir. M. Verhaegen
- dr.-ing. S. Wahls
- dr.ir. R. van de Plas
- dr. C. Smith (starting 1/4/2018)
- prof.dr. G.V. Vdovin
- dr. O. Soloviev
- dr. P. Pozzi
- ir. D. Wilding
- ir. P.J. Prins
- ir. R. Doelman
Theme 1: Tensor Kalman Filtering

Description: Large scale systems become extremely important in the analysis of many applications. Tensor calculus offers an mathematical way to deal with multidimensional systems. In this master thesis you have the opportunity to prototype new algorithms to solve the Kalman filtering problem for 2D systems plus time. A specialization of this problem is at hand based on the optical instrument design in our Smart Optics Lab for estimating wavefronts from CCD images. The emphasis in this Theme is on the fundamental signal processing side.


Possible MSc thesis projects:

- MSc thesis project 1.1: The design modeling of dynamical systems using tensors. What is tensor based linear state space model?
- MSc thesis project 1.2: The design of optimal Kalman filters for linear tensor state space models.
- MSc thesis project 1.3: The design of optimal Kalman filters for linear tensor state space models with nonlinear output equations.

These projects can be done in a team of 3 excellent students.

Theme 2: Optical Callibration in Lithography machines

Description: For the next generation of Lithographic processes extreme callibration techniques are required to map the inhomogeneities in wafer and reticle surfaces. Optical techniques are used to measure these inhomogeneities. The problem is that only intensity measurements are available that are related in a non-linear manner to the measurements. Nonlinear estimation techniques need to be designed and calibrated using industrial data. This project provides the student both with a fundamental and industrial challenge.

Possible MSc thesis projects:

- MSc thesis project 2.1: Modeling of nonlinear inhomogeneities on the wafer or reticle in a lithography machine.
- MSc thesis project 2.2: Design and validation of nonlinear estimation techniques.

Both projects can be done in a team of 2 students.

Recommended courses:

- SC42025: Filtering and Identification
- WI4201: Scientific Computing (mathematics Course)
- SC42030 and SC42065: Control for High Resolution Imaging
Theme: Non-linear Fourier analysis

Description: Linear frequency domain techniques are ubiquitous in engineering, mainly because of their low (computational) complexity. However, some systems require non-linear models: Their relevant dynamics behave according to a non-linear partial differential equation. An example is a so-called soliton wave that is observed in shallow water, but cannot exist in a linearised model. Simulation with a non-linear model is computationally costly. This is where the Non-linear Fourier Transform (NFT), also known as the Inverse Scattering Transform, comes into play: It allows cheap simulation. You can also use the NFT to analyse the non-linear frequency spectrum of measured data. Current research concerns algorithms to calculate the NFT and its inverse accurate enough and as efficient as possible.

Possible MSc thesis projects:

- Experimental demonstration/validation of the NLFT,
- Mathematical algorithm development,
- Efficient implementation in C code.

Recommended courses:

- SC42060: Modelling and Nonlinear Systems Theory (Obligatory)
- WI4046: Spectral Theory of Linear Operators\(^1\) (Highly recommended)
- WI4212: Advanced Numerical Methods
- WI4260TU: Scientific Programming for Engineers
- ME46040: Experimental Dynamics

\(^1\)Beware: ‘Free’ elective! Find and consult your MSc Thesis supervisor before choosing a ‘free’ elective.
Raf Van de Plas

Theme: Signal Analysis and Machine Learning Methods for Spectral Imaging Systems and Tensors

Description: Spectral imaging entails a broad range of 2-D and 3-D imaging techniques (e.g. hyperspectral optical imaging, Raman imaging, magnetic resonance imaging, imaging mass spectrometry) with applications ranging from medicine and biology (e.g. tumor detection) to material science (e.g. quality control), and from forensics (e.g. fingerprint analysis) to satellite-based remote sensing (e.g. crop recognition). A typical 2-D spectral imaging experiment consists of a grid of measurement locations or pixels covering a sample area, with an individual spectrum of measurements attached to each pixel. The resulting data structure can be considered as a three-mode array or tensor with two spatial dimensions (x and y) and one spectral dimension. These data tensors can become very large, both in terms of data footprint (multiple terabytes per imaging experiment) and in terms of data dimensionality (millions of variables per pixel). Many standard signal analysis and modeling approaches are unable to handle these size and dimensionality challenges, and the development of advanced mathematical methods for analyzing these massive data sets has become crucial to the successful application of spectral imaging in various areas. The Van de Plas lab is offering MSc thesis projects specifically in the area of imaging mass spectrometry. Imaging mass spectrometry is a molecular imaging technology that facilitates the direct detection of biomolecules such as proteins, peptides, and lipids in organic tissue. The generated data can be used to help unravel the mechanisms underlying disease and to identify possible targets for drug delivery.

Potential MSc thesis projects:

• Maximum Autocorrelation Factorization for Spectral Imaging Data Tensors
• Instrument-aware Rank Estimation for Dimensionality Reduction in Spectral Imaging
• Multivariate Analysis of Imaging Mass Spectrometry Data: Discovery of Neurodegenerative Disease Biomarkers in Murine Tissue

Student profile

• Motivated and independent student;
• Good knowledge of linear algebra;
• Programming experience (e.g. MATLAB, Python, C);
• Strong interest in the fields of signal analysis, mathematical optimization, machine learning, and dimensionality reduction;
• Experience in data mining and/or computer vision are a plus.

Contact

If you are interested in working on these topics or related areas, please contact raf.vandeplas@tudelft.nl. Please include a short description of your background (e.g. relevant courses taken) and/or prior experience (e.g. project work that might be relevant).

Recommended courses:

• SC42030 Control for High Resolution Imaging & IN4320 Machine Learning
• SC42050 Knowledge Based Control Systems & TN4101BM Medical Imaging
• AP3121 D Imaging Systems & WI4260TU Scientific Programming for Engineers
Oleg Soloviev

Theme 1: Wavefront sensor-less Adaptive Optics

Description: Nothing is worse than a blurry image! This knows everyone who wears glasses or had ever made an out-of-focus photo of something nice and interesting. But what if the object itself blurs your image whatever precise, accurate, and expensive optics you use? This is exactly what happens often in microscopy — variations in the light refraction index of the microscopic sample distort the path of the light rays and create fuzzy image in microscope. Moreover, this ray aberration depends on the sample, on the position of the point of interest in the sample, and even changes in time in in vivo microscopy, so it is impossible to pre-compensate it in advance with a static optical device.

The solution is to use Adaptive Optical (AO) elements, special mirrors or lenses that can change their shape or optical properties dynamically and eventually correct for the ray aberration, creating a sharp image. The necessary compensation shape can be obtained either from measuring the aberration with a wavefront sensor, or using optimisation techniques. By a number of reasons, the wavefront sensor-less methods are mainly used in microscopy. Last decade, with the advances in the AO hardware, one can state a real boom of AO in microscopy; it became a flourishing research field with a steadily growing number of practical applications in neuroscience, biology, and medicine, which require fast, accurate, and robust aberration compensation. In our group students get a unique opportunity to work on the cutting edge of science and technology and to contribute to the fascinating field of AO.

Possible MSc thesis projects:

- **Woofer-twitter optimisation**
  Suppose one has a wavefront sensor-less setup with two AO elements (often called woofer and tweeter). There will be some modes coupling between them (corresponding to lines of equal wavefronts in the joint space of the mirror control signals). The project goal is to find out how this will affect the minimisation algorithms (model-less and model-based). The project can be done theoretically, or with numerical or physical experiment.

- **Wavefront sensor-less self-calibration via optimisation**
  In AO wavefront sensor-less system one can use either slow model-less optimisation algorithms or faster model-based algorithms. The later require knowledge on the correlation coefficients between the gradients of the response functions of the adaptive element. The coefficients are calculated often either theoretically or using a separate optical arm with a wavefront sensor. Both methods are prone to errors caused by the alignment and non-common path errors. The idea of this project is to extract the cross-correlation coefficients from the model-less optimisation.

Recommended courses:

- SC42030 Control for High Resolution Imaging
- SC42065 Adaptive Optics Design Project
- SC42025 Filtering & Identification
Paolo Pozzi

**Theme 1: Adaptive optics techniques for confocal light-scanning fluorescence microscope**

*Description:* The confocal scanning microscope is an advanced form of fluorescence microscope widely used by biologists and clinicians around the world. The microscope works by scanning a point of illumination through a three-dimensional samples to obtain a very high resolution image collecting the fluorescence light through a tiny pinhole. Any optical inhomogeneity results in a loss of signal that greatly degrades the quality of the images. Adaptive optical components can correct for these so-called aberrations, but this still require the development of new correction schemes and techniques.

*Possible MSc thesis projects:*

- Image optimisation in highly parallelised scanning microscopy systems
- Anisoplanatic correction of aberrations in a confocal microscope

**Theme 2: Adaptive optics using refractive devices**

*Description:* Most adaptive optics today is done using reflective components, this has a number of disadvantages compared with refractive elements, such as the size and complexity of the optical setups. Adaptive optics can be made easier to implement by the use of an adaptive lens to correct for the phase aberrations. These devices require new control strategies for their use in the correction of images.

*Possible MSc thesis projects:*

- Control strategies for refractive adaptive components

**Recommended courses:**

- SC42030 Control for High Resolution Imaging
- SC42065 Adaptive Optics Design Project
- SC42025 Filtering & Identification
Dean Wilding

Theme 1: Adaptive optics techniques for light-sheet fluorescence microscope

*Description:* The light-sheet microscope is an advanced form of fluorescence microscope commonly used to study the development of organisms and disease. The microscope is designed to work with larger three-dimensional samples that make it strongly affected by the effects of optical inhomogeneity, resulting in blurred and misleading images. Adaptive optical components can correct for these inhomogeneities, but this still requires the development of new correction schemes and techniques.

*Possible MSc thesis projects:*

- Development of model-based wide-field sensorless adaptive optics techniques
- Feedback-based optimization of light-sheet illumination profiles
- Phase retrieval for wavefront sensing and correction in light-sheet microscopy

Theme 2: Computational Microscopy

*Description:* The price of computing is now significantly cheaper than the price of good optical components. Through the modelling and knowledge of optical systems, it is possible to detect and correct for the errors introduced by cheaper and poorly constructed optical set-ups. This means that a functioning microscope can now be made for significantly less money enabling greater use of these devices in low-resource settings.

*Possible MSc thesis projects:*

- Computational correction of anisoplanatic aberrations in microscopic samples
- Low cost diffraction-limited bright-field microscopy through chromatic aberration

**Recommended courses:**

- SC42030 Control for High Resolution Imaging
- SC42065 Adaptive Optics Design Project
- SC42025 Filtering & Identification
Background: Unfiltered images from ships’ navigation radar reveal a lot of information about ocean waves. See Figure 2 for an example. Due to the principle of radar (the measurement location is derived from the time it took for the electromagnetic pulse to travel to the target and back), one gets a received signal value for every location within the maximum range of the radar, regardless the fact that an ocean wave to some extent blocks the view of the radar directly after that wave, a phenomenon which is referred to as ‘shadowing’.

Although geometrically speaking it is easy to determine whether a region is shadowed or not, this distinction is less obvious from just the magnitudes of the received radar data. In practice one sees low reflection values at regions that are most probably shadowed but the question is: below which value of the received signal one should consider the data to be shadowed? A related question is: can we derive the wave heights from the data, from the behaviour of the shadowing.

Next Ocean: Next Ocean is a young start up spinned off from research at TU Delft. They aim to make a tool that predicts wave induced ship motions, real time, on board, in order to make offshore operations safer. Their office is at Offshore and Energy Accelerator ‘The Buccaneers’ at the Paardenmarkt, Delft, where they have a work place available.

Possible MSc thesis projects:
- Estimate shadowing and wave heights from radar data. The project will be carried out at Next Ocean.

Recommended courses:
- ME41030: 3D Robot Vision (or any other course on image processing)
- ET4169: Microwaves, Radar & Remote Sensing
- EE4C03: Statistical Digital Signal Processing and Modeling

Beware: ‘Free’ elective! Find and consult your MSc Thesis supervisor before choosing a ‘free’ elective.
Theme 1: Robust structured control

**Description:** A common design approach for (LTI) feedback control is a state-feedback controller. However, as state information is not always available for feedback, measurements are used to estimate a state (for example with a Kalman filter), and this estimated state is used for control. In practice, there is an economical cost to the use of sensors, actuators and communication between them. The question whether the sensors, actuators and communication are **necessary** to control the system with sufficient performance is usually not taken into account in control design. And if not all of them are necessary, which ones are? How does the cost of the equipment compare to the performance that can be achieved? These are some of the questions you try to answer in structured control design. The contents of any of the thesis projects here are a mix between systems theory, robust control, and optimization.

**Possible MSc thesis projects:**
- Distributed robust estimation
- Optimal sensor and actuator placement under system uncertainty

Theme 2: Online wavefront-sensorless wavefront estimation and correction

**Description:** If we place a camera in the path of light of an optical system, what we measure is the intensity (the squared absolute values) of the complex-valued optical field. If an aberration is introduced in the path of the light, the image that is obtained is distorted and blurred. Using a deformable mirror and knowledge of the aberrated wavefront we can compensate for the disturbance and obtain a sharp image. The knowledge of the aberrated wavefront can be obtained with a wavefront sensor, by estimating the phase of the optical field. However, the use of such a sensor can give practical problems, so in our group we look into algorithms that estimate the aberrated wavefront based on the intensity measurements of the camera.

The applicable algorithms for estimating the wavefront can be judged based on accuracy of the solution and the speed by which it can be obtained. The aim of our research is to estimate a slowly time varying wavefront, based on intensity measurements, quick enough to compensate them with a deformable mirror.

The contents of any of the thesis projects here are a mix between imaging systems, estimation, and optimization.

**Possible MSc thesis projects:**
- Simulated closed loop wavefront correction based on intensity measurements, investigating computational speed and accuracy.
- Validation on an optical bench of said algorithms.

**Recommended courses:**
- SC42030 Control for High Resolution Imaging
- SC42065 Adaptive Optics Design Project
- WI4226 Advanced System Theory
Hybrid, Adaptive and Nonlinear

- prof.dr.ir. B. De Schutter
- dr.ir. A.J.J. van den Boom
- dr.ir. S. Baldi
- dr.ir. E. Steur
- dr. S. Grammatico
- prof.dr.ir. N. van der Wouw
- dr.ir. J. Sijs
- dr. M. Alirezaei
- dr.ir. M. Mendel
- dr. J.R. Domínguez Frejo
Bart De Schutter

Theme: Hybrid Control and Intelligent Transportation Systems

Description: Main research interests: large-scale transportation networks (in the wide sense of the word), infrastructure networks, multi-level control, multi-agent systems, discrete-event systems, hybrid systems, traffic control, and optimization.

Possible MSc thesis projects:
The proposed MSc topics involve the following directions:

- Multi-level and multi-agent control of large-scale systems
- Control of discrete-event systems and hybrid systems, in particular max-plus and piecewise-affine systems
- Control of transportation networks
- Control of intelligent infrastructure networks (water, electricity, energy, logistics)

Both more fundamentally oriented projects can be selected as well as more application-oriented ones. In the latter context, some examples of specific projects are:

- Robust model-based predictive control of smart energy systems
- Distributed robust model-based predictive control for the car-as-power-plant
- Multi-level predictive traffic control for large-scale urban networks
- Train scheduling and maintenance planning
- Reduction of traffic emissions using model predictive control
- Optimization-based control of large-scale water networks

Recommended courses

- SC42055 Optimization in systems and control
- SC42075 Modeling and control of hybrid systems
- SC42040 Adaptive and predictive control
- Courses on distributed control
- Courses on transportation
Theme 1: Model predictive control of discrete-event systems

Description: Model predictive control (MPC) is a very popular controller design method in industry. An important advantage of MPC is that it allows the inclusion of constraints on the inputs and outputs. Usually MPC uses linear discrete-time models. In the suggested final MSc thesis projects we extend MPC to a class of discrete-event systems. Typical examples of discrete-event systems are: flexible manufacturing systems, telecommunication networks, traffic control systems, multiprocessor operating systems, and logistic systems. In general models that describe the behavior of a discrete-event system are nonlinear in conventional algebra. However, there is a class of discrete-event systems - the max-plus-linear discrete-event systems - that can be described by a model that is “linear” in the max-plus algebra. We have further developed our MPC framework for max-plus-linear discrete-event systems and included the influences of noise and disturbances.

Possible MSc thesis projects:

- Stochastic model predictive control of (switching) max-plus linear systems.
- The scheduling of discrete event systems based on switching-max-plus linear models. Scheduling is crucial in various applications, such as railway networks, production systems, baggage handling, legged locomotion, container handling and paper handling in printers.
- Performance analysis and reformulation of MILP based model predictive scheduling algorithms.

Theme 2: Modeling and control of hybrid (max-min-plus-scaling) systems

Description: In this theme we are interested in hybrid systems that can be described by models in which the operations maximization, minimization, addition and scalar multiplication appear. This class of max-min-plus-scaling (MMPS) systems is equivalent to the class of piecewise affine systems. Our current research in this context is focussed on developing minimal canonical models for this type of systems, and on extending the approach to other classes of hybrid systems.

Possible MSc thesis projects:

- Stochastic model predictive control of max-min-plus-scaling systems.
- Canonical forms and minimality in different classes of piecewise affine systems.

Recommended courses:

- SC42040 Predictive and adaptive control
- SC42075 Modeling and control of hybrid systems
- WI4062TU Transport, Routing and Scheduling
Simone Baldi

Theme 1: Control of Multimodal Uncertain Systems

Description: Many systems can behave according to different modes, but it is not always trivial to understand from data which mode is active and when a system switches from a mode to a different one. This theme aims at developing novel adaptive controllers with Multiple Models, Switching, Tuning for a set of more and more general complex systems (including input-saturation and multilevel control).

More info on my website: http://simonebaldi.my-board.org

Keywords: adaptive switching control, multiple models, reconfiguration.

Prerequisites: research-oriented attitude, adaptive control, Lyapunov stability theory, hybrid systems.

Possible MSc thesis projects:

- Adaptive control with multiple models
- Adaptive control of piecewise affine systems
- Adaptive control of slowly switched systems

Theme 2: Adaptive Optimal Control for Hybrid Uncertain Systems

Description: What to do when the system we want to drive toward optimal performance is not only uncertain, but also hybrid (e.g. with input saturation, switchings to different modes, piecewise affine dynamics)? This theme aims at developing nearly-optimal control law that can adaptively learn and drive the system toward optimal behavior.

More info on my website: http://simonebaldi.my-board.org

Keywords: hybrid systems and control, adaptive optimal control, dual adaptive control, approximate dynamic programming.

Prerequisites: research-oriented attitude, adaptive control, Lyapunov stability theory, optimal control theory.

Possible MSc thesis projects:

- Cognitive adaptive control
- Semidefinite programming-based adaptive control

Recommended courses (in order of importance):

- SC42040 Adaptive and Predictive Control
- SC42075 Modelling and Control of Hybrid Systems
- SC42050 Knowledge Based Control Systems
- SC42100 Distributed and Networked Systems
Theme 1: Synchronous oscillations in networks of dynamical systems

Description: Synchronization in networks of interacting systems (species, entities, ...) is frequently observed in nature and finds many interesting applications in engineering. Examples include the simultaneous flashing of fireflies, the synchronized release of action potentials in networks of neurons in the brain, orbital locking in solar systems and coordinated motion in groups of robots.

The study of synchronous and patterned oscillatory activity in networks of interacting dynamical systems is very challenging as the dynamics are governed by a large number of coupled nonlinear ordinary-differential-equations or delay-differential-equations. In this theme we apply tools from nonlinear dynamics (stability and instability theory, bifurcations, ...), graph theory and linear algebra to get grip on the complex collective dynamics of such systems.

Many of the problem we work on in this theme are related to (computational) neuroscience.

Possible MSc thesis projects:

- Conditions for delay-independent stability of patterns in networks of time-delay coupled systems.
- Predicting patterns of oscillation in networks of model neurons.
- Harmonic balancing methods for neural mass models.

Theme 2: Dynamics and control of biochemical circuits

Description: Bottom-up engineering of biochemical circuits can provide valuable information about the precise functioning of biological cells and systems. This approach results ultimately in procedures for the systematic design of biochemical actuators and reporting systems, which can be used, for instance, for making intelligent medicine.

We consider modular biochemical circuits for creation of sensors and actuators. Each module performs computations using DNA replication, nicking, and degradation. The modules can activate or de-active each other. In addition modules can activate themselves (auto-catalysis).

With this paradigm we recently build a biochemical toggle-switch. The goal of the present research is to gain more insight in the dynamics of this switch.

Possible MSc thesis projects:

- Design of (adaptive) observers for a biochemical toggle-switch
- Model reduction of a biochemical toggle-switch

Recommended courses:

- SC42060 Modelling and Nonlinear Systems Theory
- SC42015 Control Theory
Sergio Grammatico

Theme 1: Game theoretic distributed control

*Description:* A “game” is the mathematical description of a collection of autonomous decision making agents (e.g. humans, intelligent robots and software, autonomous cars) that share resources and interact for their well being. In a game theoretic context, we shall analyze and design distributed control strategies that the agents can use to adapt their behavior and reach optimal decisions. Within a game theoretic framework, we can address both agents that cooperate to reach a common goal, and selfish agents with their own individual goals.

*Possible MSc thesis projects:*

- Distributed noncooperative equilibrium seeking
- Semi-decentralized control of selfish agents
- Mixed-integer noncooperative games
- Wily agents in noncooperative games

Theme 2: Complex nonlinear multi-agent systems

*Description:* Modern society relies on complex systems, especially power grids, transportation systems, social and information networks. “Complexity” emerges from the presence of selfish decision making agents (e.g. humans, intelligent robots and software, autonomous cars) and network resources to be shared. In specific application domains of complex multi-agent systems, we shall analyze nonlinear multi-agent dynamics and design optimal control strategies to lead the collective agents behavior towards an efficient and safe system equilibrium.

*Possible MSc thesis projects:*

- Autonomous driving on highways
- Smart charging of plug-in vehicles
- Opinion dynamics in social networks
- Information routing in wireless ad-hoc networks

Recommended courses:

- SC42055 Optimization in Systems and Control
- SC42100 Networked & distributed control systems
- SC42015 Control theory
Nathan van de Wouw

Theme: dynamics, system theory and control of nonlinear systems

Description: Main research interests: large-scale transportation networks (in the wide sense of the word), infrastructure networks, multi-level control, multi-agent systems, discrete-event systems, hybrid systems, traffic control, and optimization. Main application areas are high-tech motion systems, cooperative driving, resource exploration, and smart energy systems.

M.Sc. projects under my supervision are generally characterized by a combination of fundamental research in nonlinear systems and control with real-life applications.

Possible MSc thesis projects:
The proposed MSc topics involve the following directions:

- Point-of-interest thermal control in reticle cooling: a case study in extremum seeking at ASML.
- Heterogeneous platooning using artificial potential fields, at TNO Automotive.
- Control of respiratory systems, at Macawi/Demcon.

From time to time, I also have M.Sc. assignments for which you can spend part of your time at the University of Minnesota in the U.S.A.

Recommended courses

- SC42100 Networked and distributed control systems
- SC42055 Optimization in systems and control
- SC42075 Modeling and control of hybrid systems
- SC42040 Adaptive and predictive control
Mohsen Alirezaei

Themes: Vehicle lateral control, Vehicle dynamics, Linear & nonlinear control, Max-Plus Algebra

Possible MSc thesis projects:
The proposed MSc topics involve the following directions:

- Integrated vehicle lateral controller for full vehicle dynamic envelope (CAS, ESC,)
- Longitudinal vehicle dynamic control (ABS, ACC using artificial potential field,...)
- Nonlinear optimal control (SDRE), sliding mode control,
- Vehicle state estimation (SDREKF, EKF, KF)
- Path Planning (APF, A*, CG)

Recommended courses

- Courses on automotive, vehicle dynamics and control
- SC42100 Networked and distributed control systems
- SC42075 Modeling and control of hybrid systems
Max Mendel

Theme 1: Economics and Finance - Modelling

Description: The behavior of engineering systems is described by the same differential equations, irrespective whether they are mechanical, electrical, hydraulic, or even mixed systems such as electro-mechanical systems. The great advantage of this is that the system analysis and design of the controller can proceed independent of the physical nature of the system.

For your thesis project, you will apply the methods for modelling mechanical systems to economic and financial systems, with the goal of incorporating economics within the purview of controls. Historically, this was also how models of electronic system were developed. The idea is to identify analogous concepts in economics to those in mechanics, comparable to how voltage/current in electronics are identified as analogous to force/velocity in mechanics.

Topic scopes for MSc thesis projects:
- Classical Mechanics
  - Newtonian methods for classical demand and supply
  - Lagrangian and Hamiltonian for utility and profit.
- Thermodynamics
  - Statistical mechanics for uncertainty and risk
- Other
  - Discrete-time for non-continuous discounting
  - Max-Plus for economic-equilibrium.

Theme 2: Economics and Finance - Control

Description: One great feature of applying mechanics to economics is that many abstract concepts in mechanics obtain a familiar interpretation in economics. For instance, momentum is analogous to price and kinetic energy analogous to profit. This carries over to controller design, where various approaches can be identified with no-arbitrage conditions, hedging, internal rates of return and valuation analysis and others.

For your thesis project, you will interpret a control methodology in economic terms and derive policies and strategies for optimal economic behavior.

Topic scopes for MSc thesis project:
- Classical control
  - Laplace domain and discount rates
  - Laplace transform and valuation
  - Frequency and volatility
  - Pole placement and IRRs
- Modern control
  - HJB and profit maximization
  - Lyapunov functions and economic cost minimization
  - Pontryagin’s minimum principle and utility maximization

Recommended courses: A background in economics or finance is recommended.
José Ramón Domínguez Frejo

Theme: Freeway traffic control

Description: Traffic congestion on freeways is a critical problem due to its negative impact on the environment and many other important consequences like delays, waste of fuel, higher accident risk probability, etc. Freeways were originally conceived to provide virtually unlimited mobility to road users. However, the continuous increase in car ownership and demand has led to a steady increase (in space and time) of recurrent and non-recurrent freeway congestion, particularly within and around metropolitan areas. The construction of new freeways is not always a viable solution that can be implemented in the short term due to technical, political, legal, or economic reasons.

In the last decades, a lot of research has been focused on making a better use of the available traffic infrastructure by using dynamic traffic control algorithms. These techniques use measurements of the traffic conditions (usually speeds and flows) over time and compute dynamic control signals (like variable speed limits and/or ramp metering rates) to influence the behavior of the drivers and to generate a response in such a way that the performance of the network is improved, by reducing delays, emissions, fuel consumption, etc.

Possible MSc thesis projects:

- **Identification and automatic detection of accidents and other unexpected capacity decreases on freeways:** This project studies the selection or proposal of triggering conditions for accident detection on freeways and the calibration, simulation and validation of macroscopic traffic flow models with decreased capacity.

- **Economic and social benefits of Intelligent Transportation Systems (ITS) on freeways:** The first goal of this project is to model the economic and social benefits of the reduction of emissions, fuel consumption, risk of accidents and total time spent by the drivers due to the application of freeway traffic control. Subsequently, it will be studied potential modifications of previously proposed traffic controllers in order to minimize economic and social cost.

- **Application of ITS techniques on the A12 freeway:** The Dutch freeway A12 between The Hague and Utrecht is equipped with variable message signs that allow to change the speed limits and with traffic lights in some of the on-ramps of the freeway (ramp metering). This project is focused on the proposal, simulation and/or analysis of the application of dynamic traffic control techniques on the A12 freeway. Previous research has demonstrated, by simulation and field tests, the potential of the application of dynamic traffic control on the A12. However, there is still a lot of work to do so the proposed M.Sc. projects will be highly relevant to the traffic control community.

Recommended courses:

- CIE4821-09 Traffic Flow Theory and Simulation
- CIE4822-09 Traffic Management and Control
- SC42055 Optimization in Systems and Control
Data-Driven Control

- dr.ir. J.W. van Wingerden
- dr. R. Ferrari
- dr.ir. M. Kok (starting 1/4/2018)
- ir. B.M. Doekemeijer
Theme 1: Data-Driven Control

Description: Subspace identification combined with predictive control has attracted considerable attention in the past years. This is mainly due to the fact that they are based on numerically reliable computations (e.g. SVD and QR). For general non-linear systems, the extensions of this class of identification approaches is far from trivial. However, by exploiting structure in the dynamics (e.g. LPV) dedicated algorithms can be developed.

Possible MSc thesis projects:
- Development of subspace ID methods for DAG systems
- Development of repetitive control methods

Theme 2: Wind Farm Control

Description: The economical feasibility of the wind energy industry greatly depends on the reliability and maintainability of new large scale wind parks/wind farms. Especially for offshore wind farms where the distributed turbines are connected into a network, the topic of predictive maintenance is crucial in the explosive growth. On a wind farm, individual optimization of each turbine is now mainly done temporally, taking the local (temporal) changes of the wind into account. The main research goal can be captured within the following phrase: Develop a new methodology for distributed fault detection, and controller reconfiguration for far offshore wind farms in a decentralized framework, where the individual wind turbines controllers are cooperating not only to optimize their local performance, but also to optimize the global performance.

Possible MSc thesis projects:
- Data-Driven Wind Farm control
- Active Power Control of Wind Farms

Recommended courses:
- SC42010 + Robust and Multivariable Control
- SC42015 + Filtering and Identification

Jan-Willem van Wingerden
Riccardo Ferrari

Theme: Fault and Cyber-attack tolerance for distributed systems

Description: Examples of distributed systems, current or futuristic, are abundant. In the case of autonomous robot formations, for instance, we can list self-driving and cooperative cars, Unmanned Aerial or Underwater Vehicles (UAVs and UUVs), airplane and satellite formations, robot swarms and similar examples. Or, if we look at critical infrastructures, we can name smart grids. Such distributed systems are expected to provide outstanding functionalities and positively influence our life and society. But they will need to do so while guaranteeing exceptional levels of safety, especially when the general public is involved. Threats to the safe operation of such distributed systems may come not only from external sources, such as changed or unfavourable environmental conditions or exogenous traffic and vehicles, but from internal sources as well. This last category includes faulty nodes, as the result of normal or accidental break down, or otherwise misbehaving ones, for instance due to malicious cyber-attacks directed at disrupting the service provided by the system.

Possible MSc thesis projects:

- **A RC car based multi-robot ensemble** As an addition to the current robots available at DCSC labs, we plan to implement a multi-robot autonomous ensemble based on reduced scale RC cars. The objective of the thesis is to design a basic distributed controller in order to achieve platooning and implement the possibility to inject in the cars artificial faults or misbehaviours, in order to simulate a cyber attack. Later, a fault and attack detector will be implemented.

- **Dynamic watermarks for cyber attack detection and identification** Cyber attacks are qualitatively different from normal faults. Attacks are active and knowledgeable, and executed in a way to avoid detection. Attackers, for these reasons, are usually called adversary. A promising technique for detecting stealthy attacks is to introduce a watermark, that is an additional signal that is difficult to detect and remove. The goal is to easily detect any tampering with legitimate signals due to the attacker presence. The scope of the thesis is to investigate the performance of different kind of watermarks, namely linear vs. non-linear, additive vs. multiplicative.

- **Data-driven Fault Diagnosis and Failure Prediction** Inefficient maintenance policies are one of the culprits for time and economic waste in the industry. Predictive maintenance is based on mathematical models and field data, and allows to predict when a given component or machine will fail or need maintenance, thus allowing to plan it in an optimal way in advance. In this thesis, mathematical models for fault diagnosis and prediction will be developed from plant data. There is the possibility to collaborate with renowned industries in the Electronics or Energy sector in The Netherlands and work with actual plant data.

Recommended courses:

- SC4092: Modelling and Nonlinear Systems Theory
- SC42025: Filtering & Identification
Theme: Closed-loop wind farm control

Description: Current practise in wind farms is a situation where each turbine tries to capture as much energy as possible for itself. However, due to the formation of wakes (slower, turbulent wind) behind an operating turbine, this “greedy control” approach has appeared suboptimal. Namely, the more energy an upwind turbine extracts from the wind, the stronger the wake, and the less power a downstream turbine captures. In wind farm control, we use open-loop and closed-loop control methods to find the optimal control settings for the turbines inside a farm to maximize the total power generation, and/or minimize the fatigue loads on the turbine structures.

Possible MSc thesis projects:

- **Extending an existing steady-state wind farm model (Gebraad et al. 2016, Wind Energy) to include wake delay dynamics, and synthesizing a closed-loop control solution using this dynamic model.** A recent trend in wind farm control is to use steady-state models in an open-loop sense to optimize the control settings (i.e., yaw angles) of the turbines every 10 minutes or so (Fleming et al. 2017, Wind Energy Science). However, these models ignore any time delays or dynamics, which are obviously present in wind farms. Including wake delay dynamics and synthesizing a predictive control solution with this model has real potential to increase model accuracy, reduce the timescale of control, and finally improve wind farm performance.

- **Distributed estimation and Kalman filter fusion for a large-scale dynamic wind farm model.** At TUDelft, we have a CFD-based wind farm model with in the order of $10^3 - 10^4$ states, which we aim to use for model predictive control. One important task in this closed-loop solution is accurate and fast state estimation. Due to the large computational effort in a regular (E)KF, distributed KFs are considered. This project is possibly in collaboration with dr.ir. Benjamin Noack from the Karlsruhe Institute of Technology (KIT).

- **Online model adaption and wind farm supervision.** A recent trend in wind farm control is to use steady-state models in an open-loop sense to optimize the control settings (i.e., yaw angles) of the turbines every 10 minutes or so (Fleming et al. 2017, Wind Energy Science). However, these models are very simplified, and we expect better accuracy can be achieved by closing the loop, and adapting the model parameters online using SCADA measurements from the turbines. Furthermore, wind farm supervision is desired to detect turbine underperformance, and minimize any potential losses.

Recommended courses:

- SC4092: Modelling and Nonlinear Systems Theory
- AE3W02TU: Introduction to Wind Energy (Optional)
Networked Cyber-Physical Systems

- dr.ir. T. Keviczky
- dr.ir. M. Mazo
- dr.ir. P. Mohajerin Esfahani
- dr. G. Giordano
- dr. A. Tejada Ruiz
- ir. C.F. Verdier
Theme 1: Distributed control of cooperative mobile robots

(mobile sensor network applications, indoor quadrotor formation flight) Groups of mobile robots capable of communicating with one another to collaboratively achieve a common goal, often referred to as Robotic Networks, offer great promise in applications ranging from underwater and space exploration, to search, rescue, and disaster relief, monitoring and surveillance, logistics automation, and high-performance agricultural systems (e.g., autonomous harvester fleets). Distributed, cooperative control is a key enabling technology for such multi-agent systems. The main goal of this project is to develop distributed algorithms to tackle the collaborative control or estimation problems in one of the above realistic scenarios. The newly developed distributed methods will be then applied and evaluated on a mobile robot testbed in the DCSC Networked Embedded Robotics Lab. Part of the project can be formulated as a software and hardware development activity of the experimental setup. Alternatively, distributed controllers can also be developed for a group of Parrot or DJI quadrotors based on computer vision or data from a distributed sensor network, which could simulate proximity operations in space.

Theme 2: Distributed Model Predictive Control for climate control in high-performance buildings and greenhouses

As various large-scale systems (such as critical infrastructure networks, transportation, heating ventilation and air-conditioning in buildings) require efficient and near-optimal control solutions while being able to handle important process constraints, model predictive control approaches are there to provide promising solutions. However, due to the heavy communication requirements, significant computational load, and lack of flexibility, traditional centralized control architectures are often difficult to implement, or otherwise undesirable. This project aims at developing and implementing a Distributed MPC approach that is modular and would be applicable for climate control in very large greenhouses or office buildings.

Other Themes:

Theme 3: Distributed optimization for control and estimation
Theme 4: Distributed fault detection for decomposable systems
Theme 5: On-line optimization-based path planning for autonomous vehicles

Recommended courses:

- SC42075 Modelling and control of hybrid systems
- SC42100 Networked and distributed control systems.
Theme 1: Formal methods in control

Description: The use of techniques from the field of formal verification and synthesis in computer science has recently attracted much interest in the control community. These techniques are specially suited to problems combining continuous dynamics with discrete events and/or complex temporal specifications, i.e. to the analysis and synthesis of hybrid systems. Many techniques have arisen from this cross fertilisation enabling the automatic synthesis of embedded control software, or the formal verification of already designed controllers. We have developed and continue to develop software tools to automate the design of embedded controllers by combining ideas from formal verification, artificial intelligence and control theory. Within these developments we offer MSc projects to bring our theoretical developments into practice and to expand the areas of application of these techniques.

Possible MSc thesis projects:
- Efficient reachability analysis for multi-dimensional linear systems
- Identification of hybrid systems via convex optimization and SAT solving techniques

Theme 2: Networked Control Systems (NCS)

Description: Modern control systems most often implement feedback over communication networks, as opposed to more classical point-to-point dedicated channels. This has many advantages in terms of efficiency of implementations, as a single communication channel can be shared among many control (and non-control related) applications. Furthermore, with the revolution of wireless technologies, wireless NCS offer an unprecedented flexibility and ease of deployment of new control applications. However, the use of shared networks and/or of feedback over wireless channels also poses a number of challenges, e.g.: how to ensure that measurements arrive on time to the controller? or how to reduce the energy consumed by wireless sensors? We address these problems through a combination of formal mathematical approaches and principles from computing, telecommunications and control engineering. MSc projects within this theme focus on demonstrating practical benefits for NCS of advanced hybrid control techniques developed in our group.

Possible MSc thesis projects:
- Implementation of timed-automata based schedulers over CAN networks
- Event-based control systems with wireless wake-up radios

Recommended courses:
- SC42075 Modelling and Control of Hybrid Systems
- SC42100 Networked and Distributed Control Systems
- IN4073 Embedded Real-Time Systems
- IN4390 Quantitative Evaluation of Embedded Systems
- IN4387 System Validation
Theme 1: Security-aware Control Synthesis in Networks

*Description:* Computation, communication, sensing and actuation devices connected over computer networks can improve operation and performance in power systems, but this increasing reliance on cyber components makes the system vulnerable to attackers who could access these components through the computer network and thereby cause significant physical and economic damage. To prevent such scenarios, fault detection and isolation (FDI) methods for dynamical systems can be used.

*Possible MSc thesis projects:* In this project, the student will take the role of a “white hat hacker” to assess the amount of damage that could be done to the system by an attacker while the system is monitored by an FDI filter. The possible thesis tasks are

- to formulate the problem in a game theoretic setting between power system operators and potential attackers;
- to design a strategy for the attacker to maximally disturb the system while the filter residual remains below the detection threshold; and
- to introduce a countermeasure to mitigate such attacks by introducing a randomize policy at the detection process.

Theme 2: Sustainable Buildings: an Advanced Diagnosis Approach

*Description:* Buildings are required to respect the standard of energy labels. Despite these standard criteria, the real energy and comfort performance are often poor due to failure during the design, construction, and operation. Furthermore, buildings operates under different sources of uncertainty including outdoor climate, occupancy behavior, which introduces novel challenges concerning the performance and maintenance of buildings.

*Possible MSc thesis projects:* In this project we construct a diagnosis filter to continuously monitor the energy consumptions of the buildings measured through various specially distributed sensors. The possible thesis tasks are

- Modeling the building dynamics
- Design diagnosis filter specialized to identify certain abnormalities
- Validate the performance of the designed filter through the real measurements

*Remark:* This MSc project is conducted under the joint supervision of TU Delft and DWa (www.dwa.nl), and involves interesting mathematical aspects as well as practical research which would be useful as an experience for those wishing to go to industry.

**Recommended courses:**

- SC42015 Control Theory
- SC42040 Predictive and adaptive control
Giulia Giordano

Theme 1: Network-decentralised control, coordination and estimation

*Description:* Complex large-scale systems composed of a set of naturally decoupled subsystems often have to be stabilised/controlled/coordinated, to ensure the desired global behaviour, by a set of local control agents that interconnect the subsystems and thus introduce coupling. In these cases, a centralised controller that acts on, and has information about, the whole system is often impossible to implement, due to the size, the geographical sparsity and the complexity of the overall system. It is then fundamental to resort to *network-decentralised control strategies*, where each control agent, affecting a subset of the subsystems (local action), has access to the state of these subsystems only (local information). Network-decentralised estimation, conversely, aims at the synthesis of network-decentralised observers for a group of agents that, according to a communication graph, exchange information about local measurements to asymptotically estimate their own state (e.g., position in a localisation problem).

*Possible MSc thesis projects:*

- Network-decentralised coordination of moving agents (robots) with collision avoidance.
- Network-decentralised height/position estimation for cartography: infer a global map based on local information exchanges.
- Network-decentralised control of flow networks in the presence of uncertainties.

Theme 2: Structural analysis of biological systems

*Description:* Can a class of systems necessarily give rise to a particular qualitative behaviour, regardless of parameter values? This is indeed the case for many natural and biological systems: although plagued by huge uncertainties and parameter variations, their global behaviour (arising from the complex interplay of local interactions) is often astoundingly robust to environmental changes and perturbations. Structural analysis aims at assessing whether a class of systems always enjoys a given property, due to its structure (topology of the interaction graph) and not to specific parameter values. The problem is formally approached by considering a system structure (associated with a graph topology) along with qualitative assumptions (such as positivity of the variables and monotonicity of the involved functions).

*Possible MSc thesis projects:*

- “Verification” of structural properties: given a graph structure, generate random functions satisfying the assumptions and check that the property always holds.
- Simulation-based/analytical study of biological systems and chemical reaction networks.

**Recommended courses:**

- SC4025 Control Theory
- SC4015 Robust and Multivariable Control Design
- SC4092 Modelling and Nonlinear Systems Theory
Theme: Operational safety in L4 autonomous vehicles

Description: My focus is the development and introduction of technologies that support functional and operational safety in L4 autonomous vehicles (car, trucks, etc.). In a nutshell, a L4 vehicle is one that can drive itself under specific use cases (scenarios) without relying on the driver to take over in case of problems. That is, besides driving itself, a L4 vehicle must be able to safely and autonomously handle technological failures, like a blinded camera, and road hazards (e.g., a sudden cut it). The former is called functional safety, while the latter is called operational safety. From a technical standpoint, functional safety lies at the intersection of fault-tolerance and control. That is, one must understand how the design, activities, and failures of sensors, actuators, computing elements, communication networks, etc. influence the performance of the vehicle control systems. Crucially, one must develop the vehicles hardware, software, and control systems jointly to ensure the handling of faults and failures in a safe way. This confluence of fault-tolerance and control is common in aerospace and nuclear applications, but it is new to the automotive industry due to the increased focus on vehicle autonomy. On the other hand, operational safety lies at the intersection of artificial intelligence, robotics, and control. A L4 vehicle can be seen as an autonomous robot that operates in an unstructured environment and takes decisions that maximize its safety and that of the surrounding traffic participants. That is, it chooses a behavior (e.g., speed, trajectory, etc.) that minimizes the probability of hazards occurring (like collisions) under the current vehicle condition and environment. This is an open research area where much growth is expected.

Possible MSc thesis projects:

- ...

Recommended courses:

- IN4073TU Embedded real-time systems
- SC42050 Knowledge-based control systems
- SC42075 Modelling and control of hybrid systems
- CIE5805 / ME41105 Automotive systems
Theme 1: Automatic controller synthesis using genetic programming

*Description:* Controller design of complex nonlinear systems requires a lot of expert knowledge. In this theme we aim to automate the controller synthesis by means of genetic programming and apply the developed techniques on actual industrial benchmarks. Genetic programming is an evolutionary algorithm based on the principles of Darwin’s evolution theory, capable of synthesizing analytic expressions given a grammar of operations. Evolutionary algorithms start with a pool of random candidate solutions (individuals), which are encoded in a form that is easy to manipulate (e.g., a binary string). These individuals are scored on their performance using a fitness function. The fitness value determines the chance of an individual to be picked for reproduction, i.e., the creation of a new individual by mutating or swapping parts of two chosen individuals. This is repeated until a new population is formed, with the hypothesis that the overall fitness of the population increases. This procedure is repeated multiple times, until a termination criterion is met.

*Possible MSc thesis projects:*
- Feedforward control of a nonlinear wet clutch (in cooperation with Flandersmake)
- Field curvature control of an active wafer controller (in cooperation with ASML)

Theme 2: Synthesis of analytic controllers using genetic programming

*Description:* Automated controller synthesis approaches for nonlinear systems with complex tasks, such as reinforcement learning and abstraction and (bi)simulation, result in controllers that can take the form of enormous tables or expressions. While useful, these controllers cannot always be implemented in embedded hardware with limited memory. Furthermore, these controllers are very tough to be interpreted by humans. Finally, controllers from e.g., reinforcement learning approaches lack formal guarantees. To overcome these limitations, we want to take one of these synthesized controllers and use genetic programming to find a compact analytic expression that can be implemented and/or further analyzed.

*Possible MSc thesis projects:*
- Abstraction and (bi)-simulation methods are able to synthesize a controller that formally guarantee certain specifications, but it results in a controller in the form of an enormous look-up table. The goal is to find a compact analytic expression corresponding to the controller that can be implemented.
- In reinforcement learning, synthesized controllers have no formal guarantees on the specifications. The goal is to find a compact analytic controller corresponding to the synthesized controller and to formally verify the controller using verification techniques.

**Recommended courses:**
- SC42050 Knowledge based control
- SC42055 Optimization in Systems and Control
- SC42075 Modeling and Control of Hybrid systems
Cognitive Robotics (CoR)

- prof.dr.ir. R. Babuska
- dr.-ing. J. Kober
- dr. J. Alonso Mora
Theme 1: Learning Motor Skills

Description: My research focuses on the intersection of machine learning and robotics, in particular on learning motor skills for robot arms. Motor skills are a learned sequence of movements, such as walking, manipulating, or essential sports skills. A robot is traditionally (re-)programmed by hand, which results in highly efficient but regrettably also very task-specific movements. As an alternative we can imagine robots that can learn new skills on their own, which would allow them to cope with changing environments and requirements autonomously. Unfortunately, most standard, off-the-shelf machine learning approaches are not directly applicable to robotic scenarios. Currently, there are two main streams of learning approaches that have been employed in motor skill learning: imitation learning and reinforcement learning (RL).

Possible MSc thesis projects:

- RL with SEDS / CLF-DM: Can the controller parametrizations that are popular in imitation learning (SEDS / CLF-DM) be employed for reinforcement learning?
- RL with human interventions: How can interacting with a human teacher during RL be used to speed up the learning process?
- Learning to interact with humans: How can a robot best deal with the huge uncertainties about human intentions and preferences when interacting with them?
- RL with multi-modal policies: How can RL deal with multi-modal policies, e.g., a hybrid force-position controller?

Theme 2: Machine Learning for Control

Description: I am also interested in more fundamental aspects of the above mentioned machine learning techniques for control.

Possible MSc thesis projects:

- End-to-end learning versus state representation learning: Deep RL can learn directly from high dimensional inputs (e.g., video streams) but takes a long time and a huge amount of samples. What advantages and drawbacks does learning a state representation first pose?
- Learning non-stationary models: How can we learn a model of a system that changes over time (e.g., fatigue or intentional breaking) and use it for control?

Recommended courses:

There is some overlap between the courses, so pick a few of the applicable ones.

- **Robotics**: SC42020 Modern Robotics; ME41025 Robotics Practicals; SC42090 Robot Motion Planning and Control
- **Machine Learning**: SC42050 Knowledge Based Control Systems; IN4320 Machine Learning; IN4085 Pattern Recognition; CS4180 Deep Learning; IN4010 AI Techniques
Javier Alonso-Mora

**Theme 1: Mobile robotics & multi-robot systems**

*Description:* Our first research interest is in navigation, motion planning and control of autonomous mobile robots, with a special emphasis in multi-robot systems and robots that interact with other robots and humans. We contribute novel methods and solutions in the areas of collision avoidance, motion planning, formation control, vehicle routing, task assignment, aerial videography and human-swarm interaction. Building towards the smart cities of the future, we apply these techniques in various fields, including autonomous cars, automated factories, aerial vehicles and intelligent transportation systems.

*Possible MSc thesis projects:*
- Multi-robot coordination (drones, boats, cars...)
- Autonomous navigation in urban environments
- Human-swarm interaction
- Machine learning and optimal control for motion planning

**Theme 2: Vehicle routing for smart transportation**

*Description:* Ride-sharing services are transforming urban mobility by providing timely and convenient transportation to anybody, anywhere, and anytime. These services present enormous potential for positive societal impacts with respect to pollution, energy consumption, congestion, etc. Current mathematical models, however, do not fully address the potential of ride-sharing. Our goal is to develop general mathematical models and methods for real-time high-capacity ride-sharing that (i) scale to large numbers of passengers and trips and (ii) dynamically generate optimal routes with respect to online demand and vehicle locations.

*Possible MSc thesis projects:*
- Multi-modal mobility on-demand with ride-sharing
- Optimal fleet sizing for transportation with autonomous vehicles

**Recommended courses:**
- SC42090 + Robot Motion Planning and Control
- SC42100 + Networked and Distributed Control Systems
- ME41105 + Intelligent Vehicles
- Other courses which provide a good mathematical base, optimization, MPC, learning, operations research or programming.