Model Reduction for Control, from Linear to Nonlinear Systems

Dates and time

7-9; 14-9; 21-9; 28-9 2020
from 10.15-12.30

Course location

Online course

ECTS

3 ECTS if the homework is completed successfully. It is not possible to get ECTS for auditing. In order to get credits the homework must be completed.

Lecturers

Prof. dr.ir. J.M.A. Scherpen, University of Groningen
Prof. dr. K. Fujimoto, Kyoto University, Japan

Objective

The purpose of this course is to provide a basis for model order reduction for control based on balanced realizations, and treats the use of these methods at different levels (more in depth or more at an initial stage) for various types of systems, varying from linear to nonlinear, from lumped to networked to distributed systems.

The need for innovation results in a dominating trend towards analyzing and designing systems of increasing complexity. Such analysis and design cycles rely on the mathematical models of the systems. These models are thus increasing in complexity as well, both in nature (from linear to nonlinear, from lumped- to networked to distributed-parameter), and size. Complex models are more difficult to analyze and simulate. Due to this it is also difficult to develop and implement control algorithms; moreover high-order controllers are usually not wanted. This course will focus both on linear and nonlinear systems, and will provide a basis for studying and usage of balancing based model order reduction methods.

Contents

1. A brief overview of recent model order reduction techniques for linear and nonlinear, networks and distributed parameter systems.
2. Balancing for linear systems is treated from a state-space point of view, and a relation with minimality and the frequency domain is given. The relation with the Hankel operator, and error bounds and their derivation are treated. Other types of balancing, closed-loop balancing, and balancing based on dissipativity, and passivity will be treated.
3. Frequency weighting, controller reduction methods, and network reduction methods based on balancing will be treated.
4. Extensions to nonlinear systems for balancing and the corresponding Hankel operator will be treated.

5. Applications for linear systems, and motivational examples for nonlinear systems will be considered

Course materials

Lecture notes will be distributed during the course.

Prerequisites

Basic background in systems and control theory.

Homework assignments

Two homework sets will be handed out. The average grade will be the final grade for this course.

Input Design and Parameter Estimation for Non-linear Systems

Dates and time

16-11; 23-11; 30-11; 7-12 2020
from 10.15-12.30

Course location

Online course

ECTS

3 ECTS if the homework is completed successfully. It is not possible to get ECTS for auditing. In order to get credits the homework must be completed.

Lecturers

Prof dr Karel Keesman, Wageningen University
Dr Hans Stigter, Wageningen University

Objective

Optimal input design is a classical problem in the identification literature. One way to tackle this problem is through optimal parametric sensitivity control, using Pontryagin's minimum principle. Unlike the traditional open-loop input design methods, in this course the emphasis is on finding a control law that maximizes parameter sensitivities for a specific set of parameters in a general single input-single state-single output nonlinear state-space model that is affine in the input.

After designing an optimal input and feeding this to the system subsequently experimental data can be collected and parameters can be estimated, given the input and output data and a prior model structure. Alternatively, a combination of recursive parameter estimation and optimal input design is also demonstrated as an elegant strategy for successful identification of a nonlinear system model.

The objective of the course is to present a methodology for (i) the design of optimal input signals for minimum-variance estimation of model parameters in the class of low-dimensional, nonlinear, state-space models under indirect state measurements, (ii) the estimation of parameters in a dynamic, non-linear model, and (iii) the introduction of the necessary concepts to apply an adaptive optimal input design strategy to nonlinear state space models.

At the end of the course the student should be able to:

- Understand the concepts of parameter sensitivity and optimal parametric sensitivity control;
- Compute parameter sensitivity trajectories together with model output trajectories;
- Design optimal input signals for low-order non-linear systems, simulate the corresponding response and estimate the unknown parameter(s);
- Evaluate the input design and parameter estimation results;
- Use off- and online methods for parameter estimation and model structure identification.

Contents

Lecture 1 - Introduction and background

- Introduction to course
- Parameter sensitivity and the Fisher Information Matrix
- Linear regression and Least squares estimation
- Static gain observers

Lecture 2 – Optimal parametric sensitivity control

- Pontryagin's minimum principle
- Singular optimal control (SOC)
- SOC for optimal input design (OID)
- Examples

Lecture 3 - Adaptive optimal parametric sensitivity control

- Framework
- Recursive parameter estimation
- Model Predictive Control
- Adaptive OID

Lecture 4 – Identification of non-linear systems

- Introduction to non-linear parameter estimation
- Role of parameter estimation in system identification
- Real-world example

Course materials

1. Keesman, KJ, System Identification: an Introduction. Springer Verlag, UK, 2011
2. Keesman KJ and Walter E, Optimal input design for model discrimination using Pontryagin's maximum principle: Application to kinetic model structures. Automatica 50(5) : 535 – 1538, 2014
3. Stigter JD and Keesman KJ, Optimal parametric sensitivity control of a fed-batch reactor Automatica 40 (8) : 1459 – 1464, 2004.
4. Stigter JD, Vries D and Keesman KJ, On adaptive optimal input design: A bioreactor case study. AIChE Journal 52 (9) : 3290 – 3296, 2006.

Additional material distributed during the course.

Prerequisites

Notions of optimal control theory and system identification at the intermediate level. Notions of Pontryagin's minimum principle and statistical estimation uncertainty might turn out useful as well. Extra course material on these topics will be provided to take into account different entry levels. Intermediate MATLAB programming skills are also required.

Homework assignments

Two homework assignments, each one accounting for 50% of the final grade. The homework assignments, distributed at the end of the second and the fourth lecture, will consist of both mathematical and programming problem solving exercises.

System Identification

Dates and time

14-9; 21-9; 28-9; 5-10; 12-10; 19-10; 26-10; 02-11 2020
from 13.45-16.00

Course location

Online course

ECTS

6 ECTS if the homework is completed successfully. It is not possible to get ECTS for auditing. In order to get credits the homework must be completed.

Lecturers

Prof.dr.ir. P.M.J. Van den Hof, Eindhoven University of Technology
Prof.dr.ir. J. Schoukens**,** VUB, Brussels, Belgium and Eindhoven University of Technology
Dr. G. Bottegal, ASML, Eindhoven

Objective

System Identification is involved with data-driven modeling of dynamical systems. The objective of this course is to present the important system identification techniques with a special attention to prediction error methods. Time- and frequency-domain methods will be covered, as well as parametric and non-parametric approaches, with particular attention for recently developed techniques in the domain of machine learning. While the focus will be on linear time-invariant systems, extensions will be made to nonlinear systems also. We will consider both the cases of open-loop and closed-loop data as well as further extensions towards dynamic networks.Contents

1. Introduction; concepts; discrete-time signal and system analysis; estimation
2.Parametric (prediction error) identification methods - model sets, identification criterion, statistical properties
3.Parametric (prediction error) identification methods - model validation, approximate modelling, Maximum likelihood and CRLB
4. Regularization and non-parametric kernel-based identification; machine learning
5. Frequency-domain identification, parametric and non-parametric
6. Nonlinear models
7. Closed-loop identification
8. Identification in dynamic networks

Prerequisites

Calculus and linear algebra. Some knowledge of statistics and linear systems theory and/or time series analysis is helpful, but not required. The lecture notes contain useful summaries of the important notions used during the course.

Course materials

Lecture notes will be distributed during the course.

Homework assignments

The assessment of this course will be in the form of three homework assignments.

Convex Optimization and Game Theory (online)

Dates and time
17-05; 31-05; 07-06; 14-06 2021
from 13.45-16.00

Course location
Online course

ECTS
3 ECTS if the homework is completed successfully.
For online courses it is not possible to get credits for auditing

Lecturers
Dr. ing. S. Grammatico, Delft University of Technology
Dr. P. Mohajerin Esfahani, Delft University of Technology

Objective
The aim of the course is to introduce the mathematical tools for analyzing and designing (distributed) algorithms for solving (multi-agent) convex optimization problems and game equilibrium problems. The selected mathematical tools are within linear algebra, system theory, fixed point and monotone operator theory.

Contents
Lecture 1: Convex analysis
Convex sets, (strictly, strongly) convex functions, indicator functions. Set-valued mappings, normal cone operator and tangent cone operator. Subdifferential mapping. Projection operator, proximal operator.
Reference material: textbooks [3, 1].

Lecture 2: Monotone operator theory
Elements of operator theory: fixed points, zeros, contraction, averaged and nonexpansive mappings. Fixed point algorithms: Picard-Banach iteration, Krasnoselskij-Mann iteration. Zero-finding algorithms: monotone operator splitting, forward-backward algorithm.
Reference material: textbook [1], survey [4].

Lecture 3: Convex optimization
Lagrangian duality, KKT system, KKT inclusion. First-order, second-order and accelerated, algorithms. Distributed optimization algorithms. Alternating direction method of multipliers (ADMM).
Reference material: textbooks [2], [3, 1], survey [4].

Lecture 4: Monotone game theory
Nash equilibrium problem, best response mapping, variational inequality. Generalized Nash equilibrium problem, preconditioned forward-backward equilibrium seeking, forward-reflected-

backward equilibrium seeking.
Reference material: textbooks [3, 1].

Course materials

[1] H. H. Bauschke and P. L. Combettes. Convex analysis and monotone operator theory in Hilbert spaces. Springer, 2010.
[2] S. Boyd and L. Vandenberghe. Convex Optimization. Cambridge University Press, 2009.
[3] R.T. Rockafellar and R.J.B. Wets. Variational Analysis. Springer, 1998.
[4] E. K. Ryu and S. Boyd. A primer on monotone operator methods. Appl. Compt. Math., 15(1), 2016.

Prerequisites

The prerequisite knowledge consists of linear algebra, calculus and optimization at a graduate level.

Homework assignments

Graded take-home exam: mathematical proofs and numerical simulations.

Design Methods for Control Systems

Dates and time

03-05 and 10-05
from 10.15-16.00

Course location

Cursus- en vergadercentrum Domstad, Utrecht

ECTS

3 ECTS if the homework is completed successfully.
1 ECTS for auditing the course

Lecturers

Dr. ir. T. A. E. Oomen, Eindhoven University of Technology
Prof. dr. ir. J.W. van Wingerden, Delft University of Technology

Objective

The course presents "classical," "modern" and "postmodern" notions about linear control system design. First the basic principles, potentials, advantages, pitfalls and limitations of feedback control are presented. An effort is made to explain the fundamental design aspects of stability, performance and robustness. Next, various well-known classical single-loop control system design methods are reviewed and their strengths and weaknesses are analyzed. The course includes a survey of design aspects that are characteristic for multivariable systems, such as interaction, decoupling and input-output pairing. Further LQ, LQG and some of their extensions are reviewed. After a presentation of uncertainty, model design methods based on H-infinity-optimization and mu-synthesis are presented.

Contents

1. INTRODUCTION TO FEEDBACK THEORY.
-Basic feedback theory, closed-loop stability,
-Stability robustness, loop shaping, limits of performance.

2. CLASSICAL CONTROL SYSTEM DESIGN.
-Design goals and classical performance criteria, integral control,
-Frequency response analysis, compensator design, classical methods for compensator design.

3. MULTIVARIABLE CONTROL.
-Multivariable poles and zeros, interaction, interaction measures,
-Decoupling, input-output pairing.

4. LQ, LQG AND CONTROL SYSTEM DESIGN.
-LQ basic theory, LQG basic theory.

5. UNCERTAINTY MODELS AND ROBUSTNESS.
Parametric robustness analysis, the small-gain theorem, stability robustness of feedback systems,

numerator-denominator, structured singular value robustness analysis, combined performance and stability robustness.

6. H-INFINITY OPTIMIZATION AND MU-SYNTHESIS.
-The mixed sensitivity problem, loop shaping, the standard H-infinity
- Control problem, state space solution, optimal and suboptimal solutions,
-Integral control and HF roll-off, mu-synthesis, application.
A. Appendix on Matrices
B. Appendix on norms of signals and systems.

Course materials

A full set of lecture notes will be made available on the DISC course platform.

Prerequisites

Basic undergraduate courses in systems and control. Some familiarity with MATLAB is helpful for doing the homework exercises.

Homework assignments

Homework sets will be distributed via the course website. Homework is graded on a scale from 1 to 10. Missing sets receive the grade 1. The final grade for the course is a weighted average of the grades for the homework sets.

Linear Matrix Inequalities in Control (Online)

Dates and time

29-03; 12-04; 19-04; 26-04 2021
from 13.45-16.00

Course location

Cursus- en vergadercentrum Domstad, Utrecht

ECTS

3 ECTS if the homework is completed successfully.
For online courses it is not possible to get credits for auditing.

Lecturers

Prof.dr. S. Weiland, Eindhoven University of Technology
Dr. M.C.F. Donkers, Eindhoven University of Technology

Objective

Linear matrix inequalities (LMIs) have proven to be a powerful tool to approach control problems that appear hard, if not impossible, to solve in an analytic fashion. The history of LMIs goes back to the forties and their role in control became emphasized in the sixties (Kalman, Yakubovich, Popov, Willems). Contemporary numerical interior-point methods and semi-definite programming techniques are increasingly powerful and allow solving LMIs in a practically efficient manner (Nesterov, Nemirovskii 1994). Several Matlab software packages are available that allow a simple coding of general LMI problems that arise in typical control problems.

Because of the availability of fast and efficient solvers for semi-definite programs, the research in robust control has experienced a paradigm shift towards reformulating control problems in terms of feasibility tests of systems of LMIs, where properties of convexity and semi-definite programs are fully exploited to solve relevant problems in systems and control.

The main emphasis of the course is:

• To reveal the basic principles of formulating desired properties of a control system using LMIs

• To demonstrate techniques that convert a controller synthesis problem into an LMI problem.

• To get familiar with the use of software packages for performance analysis and controller synthesis using LMI techniques.

The power of this approach is illustrated by several fundamental robustness and performance problems in analysis and design of linear control systems.

Contents

1. Some facts from convex analysis. Linear Matrix Inequalities: Introduction. History. Algorithms for their solution.

2. The role of Lyapunov functions to ensure invariance, stability, performance, robust performance. Considered criteria: Dissipativity, integral quadratic constraints, H2-norm, H∞-norm, upper bound of peak-to-peak norm. LMI stability regions.

3. A general technique to proceed from LMI analysis to LMI synthesis. State feedback and output feedback synthesis algorithms for robust stability, nominal performance and robust performance using general scaling.

4. A choice of extensions to mixed control problems and to linear parameter-varying controller design, robust estimation problems or the use of multiplier techniques in control system design.

Course materials

The main reference material for the course will be an extensive set of lecture notes by Carsten Scherer and Siep Weiland. Additional reference material:

1. S. Boyd, L. El Ghaoui, E. Feron and V. Balakrishnan, Linear Matrix Inequalities in System and Control Theory, SIAM studies in Applied Mathematics, Philadelphia, 1994.
2. L. El Ghaoui and S.I.Niculescu (Editors), Advances in Linear Matrix Inequality Methods in Control, SIAM, Philadelphia, 2000.
3. A. Ben-Tal, A. Nemirovski, Lectures on Modern Convex Optimization: Analysis, Algorithms, and Engineering Applications, SIAM-MPS Series in Optimizaton, SIAM, Philadelphia, 2001.
4. G. Balas, R. Chiang, et al. (2006). Robust Control Toobox (Version 3.1), The MathWorks Inc.
5. J. Löfberg, YALMIP, http://control.ee.ethz.ch/˜joloef/yalmip.php.

Prerequisites

Linear algebra, calculus, basic system theory, MATLAB.

Homework assignments

We plan to issue 4 homework sets that include choices of theoretical and practical assignments. Full credit is received for successfully solving the assigned take-home sets.

Mathematical Models of Systems (online)

Dates and time

18/01; 25/01; 01/02; 08/02; 15/02; 01/03; 08/03; 15/03
from 10.15-12.30

Course location

Online

ECTS

6 ECTS if the homework is completed successfully. For online courses it is not possible to get credits for auditing.

Lecturers

Dr. J.W. Polderman, University of Twente
Prof. dr. H. Trentelman, University of Groningen
Prof. dr. S. Trenn, University of Groningen

Objective

The purpose of this course is to discuss the ideas and principles behind modelling using the behavioral approach, and to apply these ideas to control system design.

In the behavioral approach, dynamical models are specified in a different way than is customary in transfer function or state space models. The main difference is that it does not start with an input/output representation. Instead, models are simply viewed as relations among certain variables. The collection of all time trajectories which the dynamical model allows is called the behavior of the system. Specification of the behavior is the outcome of a modelling process. Models obtained from first principles are usually set-up by tearing and zooming. Thus the model will consist of the laws of the subsystems on the one hand, and the interconnection laws on the other. In such a situation it is natural to distinguish between two types of variables: the manifest variables which are the variables which the model aims at, and the latent variables which are auxiliary variables introduced in the modelling process. Behavioral models easily accommodate static relations in addition to the dynamic ones. A number of system representation questions occur in this framework, among others:

- the elimination of latent variables
- input/output structures
- state space representations

In the first part of the course, we will review the main representations, their interrelations, and their basic properties. In the context of control, we will view interconnection as the basic principle of design. In the to-be-controlled plant there are certain control terminals and the controller imposes additional laws on these terminal variables. Thus the controlled system has to obey the laws of both the plant and the controller. Control design procedures thus consist of algorithms that associate with a specification of the plant (for example, a kernel, an image, or a hybrid representation involving latent variables) a specification of the controller, thus passing directly from the plant model to the controller. We will extensively discuss the notion of implementability as a concept to characterize the limits of performance of a plant to be controlled. We will discuss how the problems of pole-placement and stabilization look like in this setting.

Contents

1. General ideas. Mathematical models of systems. Dynamical systems. Examples from physics and economics. Linear time-invariant systems. Differential equations. Polynomial matrices.

2. Minimal and full row rank representation. Autonomous systems. Inputs and outputs. Equivalence of representations.

3. Differential systems with latent variables. State space models. I/S/O models.

4. Controllability. Controllable part. Observability.

5. Elimination of latent variables. Elimination of state variables.

6. From I/O to I/S/O models. Image representations.

7. Interconnection. Control in a behavioral setting. Implementability

8. Stability. Stabilization and pole placement.

Prerequisites

The course is pretty much self-contained. Basic linear algebra and calculus should suffice.

Course materials

The main reference is Introduction to Mathematical Systems Theory: A Behavioral Approach by J.W. Polderman and J.C. Willems (Springer 1998 as e-book).

Nonlinear Control Systems (online)

Dates and time

18-01; 25-01; 01-02; 08-02; 15-02; 01-03; 08-03; 15-03 2021
from 13.45-16.00

Course location

Online

ECTS

6 ECTS if the homework is completed successfully. For online courses it is not possible to get credits for auditing.

Lecturers

Prof. dr. B. Jayawardhana, University of Groningen
Dr. B. Besselink, University of Groningen

Objective

The course aims at introducing methods for the analysis and control of nonlinear systems, including fundamental results on stability and dissipativity, geometric control theory as well as a set of self-contained results on the control design of nonlinear systems.

Contents

Stability and dissipativity of nonlinear control systems
Lecture 1 Introduction to nonlinear systems, nonlinear differential equations, Lyapunov stability theory, LaSalle's invariance principle
Lecture 2 Dissipativity theory, passivity, L2 gain stability, input-to-state stability
Lecture 3 Interconnected systems, passivity theorem, small-gain theorem, circle criterion

Analysis of nonlinear control systems
Lecture 4 Introduction to nonlinear control systems and fundamentals of geometric control theory
Lecture 5 Feedback linearization (relative degree, zero dynamics)
Lecture 6 (High-gain) Observer design

Nonlinear control design
Lecture 7 Control Lyapunov functions and backstepping
Lecture 8 Nonlinear output regulation theory and internal model principle

Course materials

The lecture notes will be distributed during the course.

Prerequisites

The students are expected to be familiar with linear control systems and functional analysis.

Homework assignments

There are four homework assignments (once every two lectures) that will be distributed during the lectures. Each assignment must be handed in within two weeks.

Stability, Relative Stability and Synchronization of Dynamical Systems with Time-Delay

Dates and time
29-03; 12-04; 19-04; 26-04 2021
from 10.15-12.30

Course location
Cursus- en vergadercentrum Domstad, Utrecht

ECTS
3 ECTS if the homework is completed successfully.
1 ECTS for auditing the course

Lecturers
Prof.dr.ir. W. Michiels, KU Leuven
Dr.ir. E. Steur, Eindhoven University of Technology

Objective
Time-delays are important components of many systems in engineering, economics and the life sciences, due to the fact that the transfer of material, energy and information is mostly not instantaneous. Time-delays appear for instance as computation and communication lags, they model transport phenomena and heredity and they arise as feedback delays in control loops. Since delays have a significant effect on the dynamic behavior of the system, and this effect is not always intuitive, it is important to take them explicitly into account in the mathematical model. Severe challenges in the research on time-delay systems are due to the emergence of new application fields, mainly in the area of large-scale interconnected systems and networks (e.g., analysis of neuronal networks, control of communication networks like the internet, networked control systems, distributed decision making and control).

The aim of the course is to present a detailed description of the main properties of dynamical systems subjected to time-delays, thereby highlighting differences and similarities with delay-free systems and providing insight, as well as to present an overview of techniques for the stability analysis of equilibria. Both frequency domain and time-domain methods are discussed. In the second part of the course, the emphasis is on the analysis of relative stability problems, such as consensus in multi-agent systems and synchronization. Several applications, ranging from traffic flow analysis to networks of interacting neurons, complete the presentation.

Contents
1: Introduction to time-delay systems

• Examples and applications, fundamental properties of time-delay systems (representations, existence and uniqueness of solutions, stability notions), spectral properties of linear time-delay systems
• Qualitative effects of delays in dynamical systems (instability mechanisms, limitations in control, opportunities to use delays in controllers).

2: Methods for stability analysis
• Frequency domain techniques : spectral analysis (characteristic roots and pseudospectral abscissa computation), stability regions in parameter spaces (from D-subdivision to numerical continuation, invariance properties and crossing direction of roots, algebraic and geometric techniques)
• Time-domain methods: generalization of Lyapunov's second method (Lyapunov-Krasovskii functionals, Lyapunov-Razumikhin functions) , methods based on the small gain theorem.

3: Relative stability problems
• Notions of relative stability; consensus and synchronization problems
• Synchronization of two coupled systems: synchronization manifold, stabilization mechanism, sufficient conditions, effect of coupling delays (invasive versus non-invasive coupling, synchronization conditions in terms of coupling gain and delay parameters, delay compensation)

4: Synchronization in complex networks
• Description of network, including the analysis of its graph Laplacian; relation between synchronization and the network topology, full and partial synchronization
• Examples: networks of coupled Hindmarsh-Rose neurons

Course materials

The course material will be made available during the course

Prerequisites

Basic courses on dynamical systems and control

Homework assignments

Two homework assignments will be given (at the end of Lectures 2 and 4), where the students are asked to solve exercises with pen and paper and MATLAB. Software, its documentation and supplementary course material will be made available online.