Department of

Electrical Engineering

Academic year: 2020/21

Study Guide 5SC28

Machine learning for Systems and Control

Department of Electrical Engineering

Control Systems Group (CS)

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Technische Universiteit Eindhoven University of Technology

Content

1. Introduction

This study guide explains the goals and procedures around the MSc course “Machine learning for Systems and Control” / 5SC28, which is an elective course for Master of Science students in the Systems and Control and the Electrical Engineering programs.

The study guide provides additional information w.r.t. the regular course description that is available through *Canvas* at http://canvas.tue.nl and *Osiris* at https://osiris.tue.nl.

Up-to-date information regarding the course is available in the *Canvas* system.

2. Course setup

2.1 General information

Course title	Machine learning for Systems and Control
Course code:	5SC28
Quartile:	4
Program:	MSc College S&C and EE, elective course
Type of education:	8 lectures, 8 practical sessions (Q&A workshops) combined with home study and exercise/instructions sets.
ECTS credits:	5
Course subject:	The goal of this course is to provide the student with a comprehensive overview of the main off-the-shelf machine learning techniques for black-box nonlinear model identification and control, and to give the fundamental tools for practical implementation of these techniques. By taking this course, the student masters the main machine learning based modelling and control techniques for nonlinear systems, namely kernel methods, Gaussian process regression, neural networks, deep learning and control policy learning methods and develops the required skills to implement them for online and offline learning purposes.
Lecturers:	dr.ir. Maarten Schoukens (responsible lecturer) dr.ir. Roland Tóth (co-lecturer)
Teaching Assistants:	MSc. Gerben I. Beintema
Course material:	The lecture slides act as the main source of course material. Additional supporting material is available online: • C.E. Rasmussen and C.K.I. Williams, *Gaussian Processes for Machine Learning*, the MIT Press, 2006. (http://www.gaussianprocess.org/gpml/) • Goodfellow, Y. Bengio and A. Courville, *Deep Learning*, the MIT Press, 2016. (https://www.deeplearningbook.org/) • R.S. Sutton and A.G. Barto, *Reinforcement Learning: An Introduction*, MIT Press, 2018 (http://incompleteideas.net/book/the-book-2nd.html)
Group:	Control Systems (CS), Department of Electrical Engineering.
Secretariat:	secretariaat.cs@tue.nl, FLUX 5.132, tel: 040 2472300

2.2 Learning objectives and content

The course covers the following core subjects:

- Regularized kernel-based regression and support vector machines;
- Gaussian process (GP) regression;
- Artificial neural networks (ANN) and deep learning for dynamical systems; (ANN basics, training & regularization, recurrent ANN, convolutional ANN, residual ANN, …)
- Reinforcement learning (Q-learning, Q-learning with function approximation, actor-critic methods, model internalization methods)

The course is structured in two parts. The first part discusses machine learning techniques for nonlinear model identification. First, regularized kernel-based regression is presented as an extension of standard linear regression. Then, kernel-based regression is connected to Gaussian processes, which are introduced as a probabilistic tool to build models of nonlinear systems from data. Neural network-based data-driven modeling is introduced as an additional black-box modeling tool paving the way towards deep-learning. This part will start from the neural network basics, discus the training and regularization of neural networks, and continue to discuss more advanced neural network structures such as residual, recurrent and convolutional neural networks for dynamical system modelling. The second part of the course focuses on control techniques. Building upon the first part of the course, the theory of reinforcement learning (or policy learning) is introduced as a tool for black-box online controller learning for nonlinear systems. This part covers classical Q-learning, Q-learning with function approximation, actor-critic methods and model internalization-based approaches.

The contents are complemented with practical sessions where the students can practice the contents presented during the lectures.

After completing the course successfully, the students can:

1) Provide an overview of and compare the main features of GP and ANN-based data-driven black-box modelling and model learning (fundamentals, strengths and limitations) for systems and control;
2) Explain, discuss, compare and interpret the main approaches and theoretical results for data-based model learning in the nonlinear systems and control context using GP, ANNs and deep ANNs;
3) Explain, discuss, compare and interpret the main techniques and theory for reinforcement learning based control starting from classical Q-learning up to actor-critic and model internalization-based methods;
4) Recommend and evaluate a machine learning method for a real-life application in a systems and control setting.
5) Implement, tailor, and apply the Gaussian process, (deep) neural network and reinforcement learning techniques for model and control learning on real-world systems (e.g. on an inverted pendulum laboratory setup).
6) Defend and interpret the results you obtained through the above described machine learning methods.

2.3 Position in the curriculum

Prior knowledge: **5EMA0** - Basics on statistics and optimization (or similar, BSc level)

Follow-up courses: -

2.4 Education format and evaluation

This course module is 5 ECTs and estimated to have 140 hours of workload:

Activity	Hours
Lectures	8x2
Seminars/workshops	8x2
Self-directed study (reading, exercise, etc.)	8x6
Design Assignment	50
Examination – preparation and attendance	10
Total:	140

Course organization:

The course material is divided into 7 regular lecture modules and 1 introduction module, which are covered during 8 lectures and 8 exercise modules. To assist understanding of the material, each lecture is followed by a Q&A session where the students can ask questions, receive help in solving practical problems or in the use of the software. Hence, the students are recommended to prepare for these meetings by going through the written material, learn the material covered on the slide sets and practicing the written exercises (see below).

Practical material:

Sets of written exercises, downloadable via CANVAS, are made available for practicing each of these modules and are also available for discussion during the sessions. These exercises are for training only and are not required to be handed in or graded.

The computer assignments of the exercise sessions are made available through canvas together with their solution. The week after the exercises are made available, a Q&A is organized through canvas during the regular timeslot (Wednesdays starting at 10:45). The students are expected to have solved the exercises before this Q&A session with the help of the solution examples. Remaining questions can be posted on the canvas course forum or can be addressed during this Q&A session. The Q&A session finishes at 12:30 or earlier if no questions are left to be answered.

Design assignment

The design assignment revolves around an inverted pendulum setup. A computer simulation of the real-life setup will be provided, and the students will also have access to the real-life system in the CS-Group lab (time-slot reservation and obeying any COVID regulations are required). During the assignment the students are expected to:

1. identify the system dynamics starting from data
2. obtain a policy to swing up the pendulum
3. obtain a policy to use multiple targets and move from target to target

These objectives should be obtained using the tools covered in this course (Gaussian Processes, Neural Networks and Reinforcement Learning).

Q&A sessions will be organized to discuss the design assignment progress on a group-by-group basis.

The results of the design assignment are required to be handed in in terms of a final written report (pdf format) together with the developed code. One report of 6-12 pages IEEE style is expected per group (preferably 6 pages). Additionally, each group member must submit a reflection report of max. 1 page (or max. 500 words). The due date is indicated in the course schedule (see Section 2.5).

The report is graded in terms of the following assessment criteria: systematic way of obtaining the solutions, the applied knowledge, correctness of the final solution, clarity of the presentation.

Oral exam

After the 8th week, an oral defense of the group project is held. This defense, together with the submitted project report and individual reflections is used to assess the final knowledge level of the students. The oral defense consists of a 15-min group presentation of the obtained results during the design assignment. These presentations will take place on a group by group basis. The timely submission of a design assignment project report is required to take part in the oral defense. The presentations are followed by a 30-min discussion of the *obtained results* ***and*** *the theoretical knowledge of the course content*.

The examination is a so-called open-book examination. The students can use the project report and presentation during the oral examination, together with the lecture slides or any other additional material. The students are assessed on the systematic way of obtaining the solutions, on the applied and general course knowledge, on the correctness of the final solution and on the clarity of the final report and presentation. The contribution of the individual group members is also considered through the personal reflection report and the oral defense performance.

Under the current circumstances, the examination will take place through Microsoft Teams or an equivalent platform though this will be re-evaluated and possibly adjusted during Q4.

No grades are obtained, only exam points:

Design Assignment Report and Presentation: DARP $\in$ [0, 10]

Design Assignment Implementation: DAI $\in$ [0, 10]

Theory Discussion: ThD $\in$ [0, 10]

Relative Individual Contribution: RIC $\in$ [-1, 1][1]

Final grade

The final grade is composed by the exam points RP and GP. Final Grade:

```
FP = 0.33 x DARP + 0.33 x DAI + 0.33 x ThD + RIC

if FP >= 6 then
        Min(Round(FP),10)
else
        Min(Round(FP),5)
```

Based upon the above formula, the constraint to pass the course is:

0.33 x DARP + 0.33 x DAI + 0.33 x ThD + RIC $\geq$ 6

Re-sit

A re-sit is possible using the same design assignment. Registration for the re-sit is compulsory. Achieved DARP, DAI, ThD or RIC points cannot be carried over.

[1] The Relative Individual Contribution can be larger than the [-1,1] range indicated here if large difference in the contribution to the group project or on the theoretical background knowledge are observed within one group.

2.5 Course schedule and subjects

Date	Details	Time
Wed, 21 Apr 2021	L1: Introduction & preliminaries	08:45-10:45
Wed, 21 Apr 2021	P1: Python introduction + Exercises based on L1	10:45-12:30
Wed, 28 Apr 2021	L2: Data-driven modelling: regularization, Gaussian Processes	08:45-10:45
Wed, 28 Apr 2021	Q&A session: theory & exercises	10:45-12:30
Wed, 12 May 2021	L3: Data-driven modelling: artificial neural networks	08:45-10:45
Wed, 12 May 2021	Q&A session: theory & exercises	10:45-12:30
Wed, 19 May 2021	L4: Data-driven modelling: deep learning and deep neural networks	08:45-10:45
Wed, 19 May 2021	Q&A session: theory & exercises	10:45-12:30
Wed, 26 May 2021	L5: Data-driven control: basics of reinforcement learning	08:45-10:45
Wed, 26 May 2021	Q&A session: theory & exercises	10:45-12:30
Wed, 02 Jun 2021	L6: Data-driven control: reinforcement learning with function approximation	08:45-10:45
Wed, 02 Jun 2021	Q&A session: theory & exercises	10:45-12:30
Wed, 09 Jun 2021	L7: Data-driven control: actor-critic reinforcement learning	08:45-10:45
Wed, 09 Jun 2021	Q&A session: theory & exercises	10:45-12:30
Wed, 16 Jun 2021	L8: Data-driven control: model internalization-based reinforcement learning	08:45-10:45
Wed, 16 Jun 2021	Q&A session: theory & exercises	10:45-12:30
Fri, 25 Jun 2021	Design Assignment Deadline	23:59
30 Jun - 01 Jul 2021	Oral Examination	/

Please check Canvas for an up-to-date overview of the classrooms and schedule (in Course Summary).

Attendance of the lectures or the practical sessions is not compulsory. However, students attending the practical sessions are recommended to prepare for these meetings by going through the relevant theory material and practicing the provided exercises.

2.6 Questions and feedback

The team of lecturers is available during and after the Q&A hours for individual questions, comments and feedback.

Comments and feedback can also be provided through e-mail and the *Canvas* forum. Appointments with the lecturers can be made in advance via e-mail (see recommendations below). Note that appointment by “walk in” is not possible.

To make communication more efficient we ask the students to adhere to the following recommendations:

1. Questions related to better understanding of the teaching material should be posted on the *Canvas* Forum; we will check the forum frequently and provide answers.
2. The students should read carefully the study guide to find out the information they need, before asking questions by e-mail.
3. Communication by e-mail should be reserved exclusively for the cases when information is not available in the study guide or a personal matter needs to be discussed.

Contact persons are:

dr.ir. Maarten Schoukens (m.schoukens@tue.nl): lecture material, exercises, exams, organizational issues, **primary contact**

dr.ir. R. Tóth (r.toth@tue.nl): lecture material, exercises.

MSc. G.I. Beintema (g.i.beintema@tue.nl): exercises.