Robust and Nonlinear Control Design
EEN050 - Online Course Program

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Welcome!

Department of Electrical Engineering (E2), building E, Hörsalsv. 9, floor 5.
Course is decomposed into a series of lectures, problem solving, tutoring, and lab sessions. In 2020/21 LP1 all sessions will be given online via ZOOM following the previously published timetable. However, names for room/lecture hall numbers published at TimeEdit are not valid!

- **Lecturer**: *Balazs* Kulcsar, `kulcsar@chalmers.se`,
- **Teaching assistants**:
  Angel Molina Acosta (course assistant) `angel@chalmers.se`
  Angelos Toytziaridis `angtoy@chalmers.se`
- **Online web platform CANVAS** Get registered via Student admin! Teacher and TA can not do it!
- **Administrator at E2** Madeleine PERSSON, `madelein@chalmers.se`

What do you get here? Intended Learning Outcomes(ILO)

Advanced course on control system design.

1. Understand signals and systems ”sizes” and explain the limitations of nominal Linear Time Invariant (LTI) control methods.
2. Identify and describe the most important uncertainty phenomena for SISO and MIMO LTI dynamical systems;
3. Formulate robust control objectives and understand methods for calculating them
4. Apply the theory of gain scheduled control to reach robust objectives.
5. Understand the limitations of uncertain linear or parameter scheduled control systems.
6. Analyse the stability properties of nonlinear systems;
7. Apply a few methods for nonlinear control system design and to assess the performance of the resulting design;
8. Use software tools for analysis and synthesis of nonlinear control systems, and to present and motivate their solutions;

ILOs connected to technical goals (M-A-D)

1. Modeling. Goals with **ROBUST** control design, examples. Linear Time Invariant zeros-poles. Vector and system norms. SGT, internal stability, SISO vs MIMO (ILO 1).
2. Analysis. Uncertainty in SISO/MIMO system models. Nominal/robust stability/performance, Linear Fractional Transform. Design trade-offs (ILO 2).
3. Design. Robust controller design; $\mathscr{H}_2$, $\mathscr{H}_\infty$. From full information to central $\mathscr{H}_\infty$. Lyapunov stability, Linear Matrix Inequality. Linear Parametrically Varying Control System design (ILO 3-4-5).
4. Modeling. From LPV to **NONLINEAR CONTROL DESIGN**, examples (ILO 5-6)
5. Analysis.Common nonlinearities, stationary points and limit cycles, stability, Lyapunov's method, input/output stability, passivity; phase plane analysis. (ILO 6-7).
6. Design. Relative degree, zero dynamics. Exact (Feedback) linearization. Back-stepping, passivation (ILO 7-8).

How do I get it? Course materials

s,v Lecture materials (slides, videos, solution manuals, assignments, labs)

R S Skogestad, I Postlethwaite: Multivariable Feedback Control: Analysis and Design (Cremona, chapters covered 3,4,7,8,9 recommended 5,6)

NL HK Khalil: Nonlinear Systems, ISBN: 013228024-8, second edition (Cremona, chapters covered 1,3,4,10,12,13 recommended 2,5)

Lectures over ZOOM

Lecture topics (Mondays, Thursdays).

L #	Topics	slides+chapter
1	PM, Intro, Linear systems	s+(1[R]), 4.1-4.8[R]
2	Signals and system norms	s+4.9-4.11[R]
3	Uncertainty modeling I (interconnection, weights)	s+3.8[R], 7.1-7.4[R], 8.1-8.3[R]
4	Q1, Uncertainty modeling, analysis II (layouts)	s+3.8[R], 7.1-7.4[R], 8.1-8.3[R]
5	Robust synthesis I ($\mathscr{H}_\infty$ state-feedback, $\mathscr{H}_\infty$ filter)	s
6	Q2, Robust synthesis II ($\mathscr{H}_\infty$ output feedback design)	s+8.4[R]+9.1-9.3[R]
7	Robust synthesis III ($\mathscr{H}_\infty$, $\mathscr{H}_2$ controllers)	s+8.4[R]+9.1-9.3[R]
8	Q3, LPV design I (LPV models, forms)	s+v
9	LPV design II (obs, reach, stability, LMI)	s+v
10	Q4, LPV III (LMI, state feedback LPV design)	s+v
11	NL modeling (phase-plane, stationary, limit cycles)	1, 7.1[NL]
12	Q5, NL analysis I (Lyapunov, input/output stability)	3.1,3.2,3.3[NL]
13	NL analysis II (passivity)	4,5 [NL]
14	Q6, NL synthesis I (Relative degree, zero dynamics. Exact (Feedback) linearization)	12.1-12.3[NL]
15	NL synthesis II (Tracking)	12.1-12.3[NL]
16	NL synthesis III (Back stepping), Q7, overview	13.2[NL]
17	Exam preparation: Q, Course overview	

Table: Scheduled lectures

Lectures are slide based using online streaming with ZOOM. All lectures will be recorded and uploaded to Canvas. ”Q1-7” means optional/interactive/anonymous recap quizzes, ”s”-slides, ”[R]/[NL]” - robust/nonlinear book (see course material), ”v”-video lecture **Responsible**: Balazs

Exercises over ZOOM

Exercise sessions: virtual blackboard over ZOOM assisted by computers (session 1,2,3). A computer with Matlab/Robust Control Toolbox installed is needed.

E #	Topics	task
1	Linear systems, norms	B: trace, vector norms, singular value plots, $\mathscr{H}_2$, $\mathscr{H}_\infty$norm, C: $\mathscr{H}_2$, $\mathscr{H}_\infty$norm
2	System IC	B: $P,N \Leftrightarrow$ block, LFT, C: LFT, parametric uncertainty regions
3	$\mathscr{H}_\infty$state-feedback, observers	B: MCARE, block diagram, C:MFARE
4	Output feedback $\mathscr{H}_\infty$design	weighted interconnection, 1DoF $\mathscr{H}_\infty$, $\mathscr{H}_2$design
5	LPV modeling and analysis	Modeling and stability analysis
6	NL models	phase portrait, limit cycle, stability, C: phase portrait
7	NL analysis	zero dynamics, feedback linearization
8	NL synthesis	feedback linearization, backstepping

Table: Scheduled lectures, B-blackboard over ZOOM, C-computer

Responsible: Angelos, Angel

Tutorials over ZOOM

- Come with prepared questions and examples to get the most out of your limited time slot.
- Every Thursday 8-10 am (from study week 2) a tutorial session is given (topics: assignment, lab, exercise questions).
- Each group is assigned to a **tutoring slot each week**.
- Tutorial time alone is insufficient to carry out complete solutions to the assignments!

Responsible: Angel, Angelos,

Assignments

- Group up at www.canvas.chalmers.se
- Each group consists of 3 students
- Take-home assignments are distributed to be solved by a group.
- Difficulty to group up? Contact *course assistant* on week 1. Deadline to group up Friday 6 pm, study week 1.
- Each group will be assigned to a **tutoring slot each week**

Assignments

- Distribution through course homepage
- **Pre-approval of solution is mandatory before submission (ask and obtain it from TAs at tutorial session)**
- Electronic submission via CANVAS, upload 1 solution per group
- Use the filename: `Group#-Assignment#.pdf` after getting a **preliminary oral approval**
- Notification on acceptance/rejection and feedback no later than 1 week after submission deadline.
- If the solution is rejected, there is one occasion for correction. 1 extra week is given (from notifictaion) for resubmission. Only one extra chance per assignment.

Assignments

Week	Distribution	Submission	Thursdays 8-10
1	A1		
2	A2		A, Ex,Lab
3	A3		A, Ex,Lab
4		A1(Friday 6pm)	A, Ex,Lab
5			A, Ex,Lab
6		A2(Friday 6pm)	A, Ex,Lab
7			A, Ex,Lab
8		A3(Friday 6pm)	A, Ex,Lab

Table: Schedule for tutoring assignments. ”A” - Assignment, ”Ex” - Exercise.

Responsible: Angelos, Angel

Lab sessions over ZOOM

- In LP 1 2020/2021, virtual labs. Only the simulation tasks (up to Exercise 6 in the lab manual).
- With the **same groups as the assignments**
- Lab syllabus is available via course homepage. **Preparation** to the lab assessment (week 5) up to exercise 6 in the lab manual.
- Commented m-file has to be shown and run as ”project report” during the lab assessment.
- Lab assessments ca. 20 min per group on study week 5. Assessment times are scheduled for groups over CANVAS

Week	Action
1	Lab-time registration closed (Friday 6 pm)
2	
3	Lab preparation
4	Lab preparation
5	Lab assessment on preparation Mon(9-12), Thu(13-16)
6	Relabs Mon (9-12)
7	
8	

Table: Schedule for lab.

Responsible: Angel

Requirements

1. Satisfy course project requirements=(1) submitted and approved assignments (by each groups) AND (2) lab preparation (Grading UG, pass/fail, 3.5c).
2. Pass written examination (4.0c). Exam: (check registration deadline! **Registration is mandatory**) October 27 pm, ZOOM proctored remote exam (Reexams in January and August 2021)
   - Msc students, grade 3 collect 50% of points; grade 4 collect 65% of points; grade 5 collect 85% of points.
   - Lic, PhD students, to pass collect at least 65% of points.
   - Grading TH+, 3, 4, 5 (if points are larger 85% $\rightarrow$ ☕)