TMR 4243
Marine Control Systems II – Spring 2019

COURSE DESCRIPTION

The course will cover mathematical designs of robust and nonlinear model-based control laws and observer algorithms applicable to automatic control of ships, underwater vehicles, marine structures, machinery and propulsion systems, and other marine applications.

The overall course will be based lectures, theory and simulation assignments, and several practical marine laboratory exercises.

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COURSE CONTENT

The course consists of lectures on nonlinear systems theory and nonlinear robust control and observer designs, such as:

1) Stability theory for nonlinear systems.
2) Observer and estimation theory, persistency of excitation, observability, etc.
3) Observer designs (linear and nonlinear observers, separation principle).
4) Robust nonlinear control design methods (backstepping methods, nonlinear PID and integral control, ISS designs, etc.).
5) Maneuvering control theory and path-following control designs for marine vessels (path parameterization, path generation, guidance theories, and feedback control laws).
6) Dynamic Positioning (DP) control system algorithms for thrust allocation, positioning control, and DP observer designs.
7) Adaptive control designs for nonlinear systems (adaptive backstepping, gradient methods, model-reference adaptive control, etc.).

The course will include several practical exercises and laboratory sessions on Dynamic Positioning, as a control system case study, in the Marine Cybernetics Lab (MC-Lab) using the C/S Enterprise model ship – we call it the *DP-Lab*. The students will work on these lab setups to gain hands-on experience with practical implementation of control algorithms. The lab work shall result in a project report that counts for the final grade in addition to the exam.

LITERATURE

Generic literature

For the general lectures, the lecture presentations, lecture notes, and the following literature is required reading for all.

Nonlinear control theory:

Khalil, H. K. (2015). ***Nonlinear Control – Global edition***, Pearson Education Ltd, England. Selected chapters: 1, 2, 3, 4, 8, 9.1-9.5, 9.7, 10.0-10.1, 11, 13.1-13.4.

Maneuvering control designs:

Skjetne, R. (2005). ***The Maneuvering Problem***. NTNU Ph.D. thesis 2005:1, Dept. engineering cybernetics. Selected chapters: 1.1, 1.3-1.4, 2, 3.1-3.2, 4.1-4.3.

Other relevant literature

MRAC:

Lavretsky, E. and K. A. Wise (2013). ***Robust and Adaptive Control (With Aerospace Applications).*** Springer-Verlag, London, 2013. Selected chapters 7-10. E-book: http://link.springer.com/book/10.1007%2F978-1-4471-4396-3

Arcak, M. (2007). ***Passivity as a Design Tool for Group Coordination***. IEEE Trans. Automatic Control, Vol. 52, No. 8, pp. 1380-1390. (General synchronization design methodology, where formation control is a special case)

Skjetne, R. and Fossen, T. I. (2004). ***On integral control in backstepping: Analysis of different techniques***. In Proc. American Control Conf., AACC, Boston, USA.

Anderson, B. D. O., Bitmead, R. R., Johnson, Jr., C. R., Kokotovic, P. V., Kosut, R. L., Mareels, I. M. Y., Praly, L., and Riedle, B. D. (1986). ***Stability of adaptive systems.*** MIT Press Series in Signal Processing, Optimization, and Control, 8. The MIT Press, Cambridge, MA, USA. *Passivity and averaging systems.* Chapter 2.3 (handed out in class).

Suggested literature on other specialization subjects to be agreed upon.

INTENDED LEARNING OUTCOMES

At the end of the course, the student shall be able to:

- Describe conditions for existence, uniqueness, and completeness of solutions of time-invariant (autonomous) and time-varying (nonautonomous) ordinary differential equations.
- Characterize local, global, uniform, and asymptotic stability properties of nonlinear systems in the sense of Lyapunov and various invariance theorems.
- Relate bounded perturbations to input-to-state stability (ISS) of the nonlinear system and convert this into equivalent conditions for the Lyapunov equations.
- Discuss the most common types of control objectives, define the concept of a control Lyapunov function (CLF), and apply a CLF-based methodology to design a control law according to a defined problem statement.
- Demonstrate how to design and implement a relevant state observer to fuse and filter measurements and reconstruct unmeasured states, e.g. the velocity of a marine vehicle.
- Demonstrate how to design control laws based on feedback linearization, backstepping, and integral control, how to design adaptive control laws, and how to formulate a control objective and design the control law as a maneuvering problem.
- Use the basic nonlinear control theory, control design methodology, and observer design methodology to develop a Dynamic Positioning control system for a model ship.
- To carry out laboratory work in teams, solve practical marine control problems, and to write up the results in a report with a clear and concise exposition of results, assessments, and conclusions.
- Conduct academic studies and written work in an honest and ethical manner, without any sort of plagiarism and misconduct in work assignments and project reports.

SIMULATION AND LAB EXERCISES

The students will learn verification activities of control and estimation algorithms from offline simulation to real-time laboratory testing. In between here, the students shall learn to go through the following steps:

Simulation (offline)

- **Implementation of *design model* in Matlab/Simulink and control/observer algorithms.**
  - Verify through a set of simulation test cases the correctness of the algorithms and concluded stability and performance properties for the ideal closed-loop system.
- **Implementation of higher fidelity *simulation model* in Matlab/Simulink.**
  - Verify through a set of simulation test cases the performance and robustness of the algorithms for various model uncertainties and disturbances using the higher fidelity model. If possible, find limiting conditions.

HIL (real-time)

- Implementation of a simulation model on a real-time simulation platform with real I/O.
- Implementation of a custom-built user interface with command and monitoring functions equal to the user interface for the real (lab) control system.
- Enables online interaction with the simulation.
- Verify through a set of simulation test cases the adequacy of the user interface, the communication topology, and the robustness of the algorithms when implemented and executed on a discrete computer platform.
- Verify robustness of control system with simulation of "real I/O signal" discrepancies such as noise, wildpoints, loss of signal, asynchronous sampling, etc.

Lab (real-time)

- Implementation of control /observer algorithms on a real-time experimental platform with I/O capability and a custom-built user interface with command and monitoring functions.
- Verify through a set of experiment test cases the performance and robustness of the algorithms for the application.

LECTURE SCHEDULE

Week	Time/Place	Lecture Topics	Required reading before lecture
02	Thursday 10.01 14:15–17:00 T3	**Lecture 1 – Properties and stability of time-invariant ODEs:** • Properties and phenomena of nonlinear time-invariant ODEs. • Stability of time-invariant ODEs. • Lyapunov stability characterization.	• Note on “Mathematical notations and preliminaries” • Khalil Ch. 1, 2, 3.1-3.3 • Lavretsky and Wise Ch.8.1-8.3 (alternative explanations) • Lecture presentation

03	Monday 14.01
	09:15–12:00
	T7
		Lecture 2 – Global stability of nonlinear systems:
		• Time-invariant nonlinear systems:
		   o Global Lyapunov stability.
		   o Krasovskii-LaSalle’s invariance principle (for time-invariant ODEs).
		• Time-varying systems:
		   o Global Lyapunov stability.
		   o Invariance theorems time-varying ODEs.
			• Khalil Ch. 3.4-3.7, 4.1
			• Lavretsky and Wise Ch.8.4-8.8 (alternative explanations)
			• Lecture presentation.

03	Thursday 17.01 14:15–17:00 T3	**Lecture 3 – Nonlinear control:** • Nonlinear control design. • Stabilization • Input-to-State Stability (ISS).	• Note on “Some inequalities” • Khalil Ch. 8, 9.1-9.2, and 10 (intro) • Khalil Ch. 4.2-4.4 • Lecture presentation
04	Monday 21.01 09:15–12:00 T7	**Lecture 4 – ISS and Feedback linearization:** • Input-to-State Stability (ISS). • Minimum vs. nonminimum phase system. • Zero dynamics (internal dynamics). • Feedback linearization.	• Khalil Ch. 4.2-4.4, 9.1-9.4 • Lecture presentation
04	Thursday 24.01 14:15–17:00 T3	**Lecture 5 – Backstepping:** • Control Lyapunov Function (CLF). • Normal backstepping. • LgV backstepping.	• Khalil Ch. 9.7 and 9.5. • Skjetne (2005). Ch. 4.1 • Lecture presentation
05	Monday 28.01 09:15–12:00 T7	**Lecture 6 – Observer designs:** • Luenberger observer • Separation principle • Nonlinear observers	• Khalil Ch. 11 • Lecture notes on “DP observers” • Lecture presentation
05	Thursday 31.01 14:15–17:00 T3	**Lecture 7 – Maneuvering control design:** • The maneuvering problem statement. • Path generation. • Maneuvering control design.	• Skjetne (2005). Ch. 1.1, 1.3-1.4, 2, 3.1-3.2 • Lecture presentation
06	Monday 04.02 09:15–12:00 T7	**Lecture 8 – Maneuvering examples:** • Some maneuvering theory and examples. • Matlab implementation of the hybrid path generator. • Example design: LOS guidance system.	• Lecture presentation • SW functions

06	Thursday 07.02 14:15–17:00 T3	**Lecture 9 – DP control system:** • DP control design model • Thrust allocation • DP observer • DP control law • DP maneuvering control	• TBA
07	Thursday 14.02 14:15–17:00 T3	**Lecture 10 – Disturbance rejection and integral action:** • Constant disturbance rejection by integral action • Internal model principle and disturbance rejection by disturbance estimation.	• Khalil Ch. 13.1-13.4 • Lecture presentation
09	Thursday 28.02 14:15–17:00 T3	**Lecture 11 – Adaptive control:** • Direct and indirect adaptive control. • UCO and PE (Persistency of Excitation). • Estimation by adaptive control.	• Lecture notes and presentation. • Extract from Anderson et al (1986) on "Stability of adaptive systems" • "Work note: Stability lemma"
10	Thursday 07.03 14:15–17:00 T3	**Lecture 12 – Adaptive backstepping:** • Adaptive backstepping example for DP. • Scalar adaptive backstepping. • 2- and 3-step vectorial adaptive backstepping.	• Skjetne (2005). Ch. 4.2 • Lecture notes and presentation
15	Thursday 11.04 14:15–17:00 T3	**Lecture 13 – Course summary**	• All

LEARNING ASSESSMENT

The grade is based on:

- 60% on the written exam.
- 40% on the theory, simulation, and laboratory reports.

Final exam

There will be a final written exam at the end of the semester, counting 60% on the final grade.
Date: May 14th, 2019, @ 09:00-13:00.

EXERCISES AND PROJECTS

Knowledge of Matlab®, Simulink®, and LabVIEW® are needed in exercises and lab works. See http://www.ivt.ntnu.no/imt/software/matlab and the Matlab course posted on *Blackboard*. See also the resources made available to us by Mathworks:

1. MATLAB self-paced training courses included with NTNU license; registration link: https://trainingenrollment.mathworks.com/selfEnrollment?code=QXJ2KLU3JVIN

2. Subject specific tutorials for control, signal processing: https://se.mathworks.com/academia/student_center/tutorials/?s_tid=acport_tut_sp_til

3. Courses repository with MATLAB in other universities: https://se.mathworks.com/academia/courseware/?s_tid=acport_cw_ep_til

4. MATLAB Hardware support for Project based learning using Arduino, raspberry pi etc.: https://se.mathworks.com/academia/hardware/?s_tid=acport_hw_ep_til

Week	DP-Lab topics
11	**Case A: Thrust allocation and joystick control:** • Thrust allocation for 3DOF DP applications. • Joystick control of surge/sway/yaw as opposed to individual thruster control by manual levers. • Implementation of combined joystick and thrust allocation for a DP manual joystick mode.
12	**Case B: 3 DOF DP Observer algorithm:** • DP observer design • Passive DP observer for estimation of position, velocity, and bias vector. • Implementation of DP observer for state filtering and real-time estimation of velocity and bias for C/S Enterprise. • Dead-reckoning and fault tolerance.
13	**Case C: 3 DOF DP Control law:** • Nonlinear DP control design by PID. • Nonlinear DP control design by Backstepping. • Implementation of DP control law(s) for positioning of C/S Enterprise. • Robustness to waves and disturbances? • Tentative: Design and implementation of DP maneuvering control.

All answers to assignments and reports to be submitted on *Blackboard*, where also the deadlines are indicated. The homework assignments are not mandatory but should be delivered on *Blackboard* for feedback. Keep all submitted reports short and to the point.

Confer with teaching assistant (vitass) for specific information on the scope and formalities on the lab work and related theory and simulation assignments.