Control theory

Course description sheet

Basic information

Field of study Mechatronic Engineering with English as instruction language **Major** - **Organisational unit** Faculty of Mechanical Engineering and Robotics **Study level** First-cycle (engineer) programme **Form of study** Full-time studies **Profile** General academic	**Didactic cycle** 2019/2020 **Course code** IMiRIMAS.Ii20K.111bf9b26c26da2370a1fd8d447df5d7.19 **Lecture languages** English **Mandatoriness** Obligatory **Block** Core Modules **Course related to scientific research** Yes

Course coordinator	Phong Dao
Lecturer	Phong Dao

Period Semester 6	**Method of verification of the learning outcomes** Exam **Activities and hours** Lectures: 42 Auditorium classes: 28 Laboratory classes: 34	**Number of ECTS credits** 9

Goals

G1	This course is designed to provide students with the knowledge and understanding of: (1) Mathematical modeling of dynamic systems and linearization of nonlinear systems; (2) Analysis and design of classical feedback control systems; (3) State-space methods for control system design; (4) Advanced controllers (e.g. model reference adaptive control, learning feedforward control); (5) Analysis and design of robust control systems; (6) Fuzzy logic control and agent-based control; (7) Model-based design tools (Matlab/Simulink, Control Systems Toolbox, PID Tuner GUI) and Fuzzy Logic Toolbox.

Course's learning outcomes

Code	Outcomes in terms of	Learning outcomes prescribed to a field of study	Methods of verification
Knowledge – Student knows and understands:			
W1	- Student knows how to model real-world dynamical systems in terms of differential equations, Laplace transform and state-space models such that they can be used for the design and simulation of control systems. - Student knows how to use flexibly system representations in the time domain (i.e. step response, state-space description), frequency domain (e.g. Bode, Nyquist and Nichols plots) and s-domain, and understands the transformations between these systems and their mutual relations.	IMA1A_W01, IMA1A_W04, IMA1A_W08, IMA1A_W09	Activity during classes, Execution of exercises, Execution of laboratory classes, Report
W2	- Student knows and understands how to design PID controllers, lead-lag compensators and feed-forward controllers for improving dynamic performances of systems by using classical control techniques such as frequency domain design using Bode plots and s-plane design using root-locus; analyse the stability of feedback systems in Bode and Nyquist plots in the frequency domain and with root-loci in the s-domain. - Student has knowledge in modern control principles: state-space control (e.g. state variable feedback, state observers, Integral control), optimal control (Linear Quadratic Regulator), optimal estimation (Kalman filter), robust control (e.g. robust PID controllers, Internal Model Control), intelligent control (e.g. Fuzzy logic control) and adaptive control (Model Reference Adaptive Control); understand the basic concepts of agents, multi-agent systems and agent-based control.	IMA1A_W04, IMA1A_W08, IMA1A_W09, IMA1A_W12	Activity during classes, Execution of exercises, Execution of laboratory classes, Report
W3	Student has knowledge in discrete-time systems (i.e. sampling, the z-transform, analysis of stability, observability) and knows how to design sampled-data control systems (e.g. lead-lag compensators, PID controllers) using three different approaches to discrete-time controller design: (1) indirect design by translating a continuous-time controller to a discrete-time controller using various approximations (or emulations); (2) direct design in z-plane using the root-locus method, or the Bode and Nyquist diagrams, and (3) direct design in discrete-time domain using state-space approach.	IMA1A_W08, IMA1A_W09, IMA1A_W10, IMA1A_W12	Activity during classes, Execution of exercises, Execution of laboratory classes, Report
Skills – Student can:			

U1	- use the basic principles and techniques for designing, analysing, implementing and evaluating controllers for linear systems in both continuous-time and discrete-time frameworks; - use of the feedback and feed-forward control structures to improve the dynamic behaviour of a controlled system and to make it less sensitive for disturbances and parameter variations and simultaneously understand the limitations of these measures with respect to stability; explain the stability of the control systems and apply stability criteria to analyse stability of control systems; - integrate the knowledge from other courses, in particular knowledge on modelling and identification of physical systems and various representations of dynamical systems, to analyse and synthesise control systems.	IMA1A_U05, IMA1A_U07, IMA1A_U10, IMA1A_U11, IMA1A_U16, IMA1A_U20	Activity during classes, Execution of exercises, Execution of laboratory classes, Report
U2	use MATLAB, Simulink and the Control Systems Toolbox for computer-assisted design, analysis, simulation and implementation of control systems.	IMA1A_U07, IMA1A_U08	Activity during classes, Execution of laboratory classes, Report
U3	- perform a survey and literature search to find materials relevant to the subject being explored; - briefly summarize, present and defend the work in an oral presentation; - prepare clear and concise reports of the work that was done in the laboratory and project; - work effectively with other students in a collaborative group to be able to obtain the overall goal assigned to the team.	IMA1A_U01, IMA1A_U02, IMA1A_U03, IMA1A_U04, IMA1A_U05	Activity during classes, Execution of laboratory classes, Report, Involvement in teamwork
Social competences – Student is ready to:			
K1	Student has ability to carry out the work in a team.	IMA1A_K02, IMA1A_K04, IMA1A_K05, IMA1A_K06, IMA1A_K07	Activity during classes, Execution of laboratory classes, Involvement in teamwork

Program content ensuring the achievement of the learning outcomes prescribed to the module

This course is designed to provide students with the knowledge and understanding of: (1) Modelling of dynamic systems and linearization of nonlinear systems; (2) Analysis and design of classical feedback control systems; (3) State-space methods for control system design; (4) Robust control system design; (5) Fuzzy logic control and agent-based control.

Student workload

Activity form	**Average amount of hours* needed to complete each activity form**
Preparation for classes	87
Lectures	42
Auditorium classes	28
Laboratory classes	34
Realization of independently performed tasks	47

Examination or final test/colloquium	2
Preparation of project, presentation, essay, report	30
Student workload	**Hours** 270
Workload involving teacher	**Hours** 104

* hour means 45 minutes

Program content

No.	Program content	Course's learning outcomes	Activities
1.	Lecture 1. Introduction to control systems (3 hrs.): * Course organisation * History of automatic control * Control system fundamentals * Examples of control systems * Steps in the design of a control system	W1, W2, W3, U1, U2, U3, K1	Lectures
2.	Lecture 2. System modelling and descriptions (3 hrs.): * Physical modelling, black-box and grey-box modelling * Modelling of dynamic systems * Modelling of mechatronic systems * Multiple views in modelling of a mechatronic system * Example: Multiple views in modelling of a DC motor * Nonlinearities * Linearization of nonlinear systems	W1, W2, W3, U1, U2, U3, K1	Lectures
3.	Lecture 3. Time domain analysis (3 hrs.): * Laplace transforms * Transfer functions and block diagrams * Time domain response of first-order systems * Time domain response of second-order systems * Response of higher-order systems	W1, W2, W3, U1, U2, U3, K1	Lectures
4.	Lecture 4. Closed-loop control systems (3 hrs.): * Closed-loop transfer function * System types and steady-state errors * PID controllers * How to implement a real-time controller in practice?	W1, W2, W3, U1, U2, U3, K1	Lectures
5.	Lecture 5. Classical design in the s-plane and frequency domain (3 hrs.): * Stability of dynamic systems * The Routh-Hurwitz stability criterion * Root-locus analysis * Design in the s-plane * The complex frequency approach * The Bode diagram * Stability in the frequency domain * Compensator design in the frequency domain * Relationship between frequency response and time response for closed-loop systems	W1, W2, W3, U1, U2, U3, K1	Lectures

6.	Lecture 6. Digital control system design (3 hrs.): * Shannon’s sampling theorem * Ideal sampling * The z-transform * Digital control systems * Stability in the z-plane * Discrete-time controller design approaches	W1, W2, W3, U1, U2, U3, K1	Lectures
7.	Lecture 7. State-space methods for control system design (12 hrs.): * State-space models * Controllability * Controllable canonical form * State feedback and pole assignment * Observability * Observable canonical form * Observer design (pole assignment) * Observer-based control (separation theorem) * Integral state-space control	W1, W2, W3, U1, U2, U3, K1	Lectures
8.	Lecture 8. Advanced controllers (3 hrs.): * Classical feedback control * Introduction to advanced controllers * Linear Quadratic Gaussian (LQG) * Model Reference Adaptive Control (MRAC) * Learning Feedforward Control (LFFC) * LQG combined with MRAC-based LFFC	W1, W2, W3, U1, U2, U3, K1	Lectures
9.	Lecture 9. Robust control system design (3 hrs.): * Introduction to robust control * Robust control systems and system sensitivity * Analysis of robustness * Systems with uncertain parameters * The design of robust control systems * Control systems with a prefilter * The design of robust PID controlled systems * The robust internal model control (IMC) system * Case studies	W1, W2, W3, U1, U2, U3, K1	Lectures
10.	Lecture 10. Fuzzy logic control (3 hrs.): * Intelligent control systems * Foundations of fuzzy logic * Fuzzy logic control * Case study: Fuzzy logic controller for position control system using asynchronous motor	W1, W2, W3, U1, U2, U3, K1	Lectures
11.	Lecture 11. Agent-based control (3 hrs.): * Agents and Multi-Agent Systems (MAS) * Applicability of Agent and MAS Technology * Applications of MAS in Control Engineering * Multi-Agent Control Systems (MACS)	W1, W2, W3, U1, U2, U3, K1	Lectures

12.	Four laboratory assignments are assigned periodically during the course. Students will need to use MATLAB including Simulink, the Control Systems Toolbox, the Fuzzy Logic Toolbox to aid in solving these assignments. Laboratory no. 1 – Classical Feedback Control Laboratory no. 2 – State-Space Control Laboratory no. 3 – Robust Control Laboratory no. 4 – Control System Design for Inverted Pendulum on a Cart ================================== ================================ Laboratory no. 1 – Classical Feedback Control Keywords: feedback control, linear time-invariant (LTI) systems, transfer functions, step response, Bode plot, Nyquist plot, root locus plot, conditionally stable systems, PID controllers, Ziegler-Nichols method, Matlab/Simulink, Control Systems Toolbox. Recommended reading: Chapters 3,4,5,6 of [1] and Chapters 4,7,8,9 of [2]. [1] Roland S. Burns, Advanced Control Engineering, Butterworth-Heinemann, 2001, ISBN 978-0-7506-5100-4. [2] Richard C. Dorf and Robert H. Bishop, Modern Control Systems, 8th edition, Addison-Welley, Boston, MA, 1997, ISBN: 978-0-2013-0864-8. This laboratory consists of 4 exercises; each exercise includes 2-5 tasks.	W1, W2, W3, U1, U2, U3, K1	Laboratory classes
13.	Laboratory no. 2 – State-Space Control Keywords: state-space models, controllability and observability, state feedback controller, state observer, pole placement, integral control, pole-zero cancellation, Matlab/Simulink, Control Systems Toolbox. Recommended reading: Chapter 8 of [1], Chapters 3 & 11 of [2], and lecture slides [3]. [1] Roland S. Burns, Advanced Control Engineering, Butterworth-Heinemann, 2001, ISBN 978-0-7506-5100-4. [2] Richard C. Dorf and Robert H. Bishop, Modern Control Systems, 8th edition, Addison-Welley, Boston, MA, 1997, ISBN: 978-0-2013-0864-8. [3] Phong B. Dao, Control Theory (RIMA-1-612-s), Lecture 07. State-space methods for control system design. This laboratory consists of 7 exercises; each exercise includes 2-6 tasks.	W1, W2, W3, U1, U2, U3, K1	Laboratory classes

14.	Laboratory no. 3 – Robust Control Keywords: feedback control, robust control, systems with uncertain parameters, system sensitivity, system stability, robust stability, robustness margins, disturbance rejection, Nyquist stability criterion, Routh-Hurwitz stability criterion, lead-lag compensator, robust PID controllers, prefilter design, Matlab/Simulink, Control Systems Toolbox. Recommended reading: Chapter 9 of [1], Chapter 12 of [2], and lecture slides [3, 4]. [1] Roland S. Burns, Advanced Control Engineering, Butterworth-Heinemann, 2001, ISBN 978-0-7506-5100-4. [2] Richard C. Dorf and Robert H. Bishop, Modern Control Systems, 8th edition, Addison-Welley, Boston, MA, 1997, ISBN: 978-0-2013-0864-8. [3] Phong B. Dao, Control Theory (RIMA-1-612-s), Lecture 04. Closed-loop control systems. [4] Phong B. Dao, Control Theory (RIMA-1-612-s), Lecture 09. Robust control system design. This laboratory consists of 4 exercises; each exercise includes 2-4 tasks.	W1, W2, W3, U1, U2, U3, K1	Laboratory classes
15.	Laboratory no. 4 - Control System Design for Inverted Pendulum on a Cart Keywords: inverted pendulum, feedback control systems, linear time-invariant (LTI) systems, transfer functions, PID controllers, automatic PID tuning, state-space models, state feedback controller, pole placement, fuzzy logic control, modelling and simulation, Matlab/Simulink, Control Systems Toolbox, PID Tuner GUI, Fuzzy Logic Toolbox. Recommended reading: Chapter 10 of [1] and lecture slides [2, 3]. [1] Roland S. Burns, Advanced Control Engineering, Butterworth-Heinemann, 2001, ISBN 978-0-7506-5100-4. [2] Phong B. Dao, Control Theory (RIMA-1-612-s), Lecture 07. State-space methods for control system design. [3] Phong B. Dao, Control Theory (RIMA-1-612-s), Lecture 10. Fuzzy logic control. This laboratory consists of 4 exercises; each exercise includes several tasks.	W1, W2, W3, U1, U2, U3, K1	Laboratory classes

16.	During these classes, students are required to solve practice exercises through applying knowledge learned from the lectures without using MATLAB/Simulink. These exercises cover the following topics: 1. Construct mathematical models for mechatronic systems. 2. Modelling of dynamic systems and linearization of nonlinear systems. 3. Design state variable feedback controllers and state observers. 4. Design sampled-data control systems. 5. Design robust PID controllers using the ITAE method. ================================ ============================== Part 1 – Modelling of Dynamic Systems and Linearization of Nonlinear Systems Keywords: nonlinear systems, inverted pendulum on cart, one-link planar manipulator, modelling and simulation, Newton's laws of motion, Euler-Lagrange method, linearization around an equilibrium point, Taylor's series expansion, linearized systems, state-space models. This part consists of 5 exercises; each exercise includes 2-3 tasks.	W1, W2, W3, U1, U3, K1	Auditorium classes
17.	Part 2 – State-Space Methods for Control System Design Keywords: state-space models, state-space coordinate transformation (similarity transform), inverted pendulum on cart, state feedback controller, state observer, pole placement, controllable canonical form, observable canonical form, modelling and simulation, Matlab/Simulink. This part consists of 3 exercises; each exercise includes 2-7 tasks.	W1, W2, W3, U1, U3, K1	Auditorium classes

Extended information/Additional elements

Teaching methods and techniques:

Lectures, Discussion, Case study, Group work, Problem based learning, E-learning

Activities	Methods of verification	Credit conditions
Lectures	Activity during classes	
Audit. classes	Activity during classes, Execution of exercises, Report, Involvement in teamwork	
Lab. classes	Activity during classes, Execution of laboratory classes, Report, Involvement in teamwork	

Additional info

Laboratory and exercise policy: - Laboratory and exercise assignments are performed in groups of two students. - Laboratory and exercise assignments will be handed out every two or three weeks. Students should solve all tasks (or questions) given in the assignments and submit reports within the prescribed time (often four or five weeks after they were assigned). No late report will be accepted except for exceptional circumstances. - Laboratory and exercise reports must be typed on a word-processor and submitted by emails as PDF attachments. Each group of two students should submit only one report (not two

identical copies) for each assignment.
Important remarks for the final exam: • This is an OPEN note/book examination. Computers and MATLAB/Simulink are required for solving some of the problems. In addition, internet may be used. • There are two parts: Part A (70 points) and Part B (30 points). • Part A consists of six tasks, which must be solved by using computers and MATLAB/Simulink. It is necessary to note that some tasks require you to explain and/or give your comments on the results obtained by using MATLAB/Simulink so that you should read the tasks and requirements carefully. • Part B has three questions, which must be solved without using computers and MATLAB/Simulink. It is important to note that you will not get any points if using computers and MATLAB/Simulink to solve these questions. In other words, Part B basically involves solving problems using hand calculation. • Each task (or question) contains a number of sub-tasks (or sub-questions) so that you should check the tasks/questions carefully to avoid forgetting to answer all sub-tasks (or sub-questions). • If a (sub-)task is required to solve by using MATLAB/Simulink then you need to write/draw on your exam papers the MATLAB code you implement, the Simulink models you create, and the resulting plots (if any). Also, don't forget to explain and discuss the results you obtain in detail. • If a (sub-)question is required to solve by hand calculation then you must complete it without using computers and MATLAB and show the detailed calculation steps and results on your exam papers. • You will perform the final exam in groups of two students (possibly in groups of three students in exception cases). Each group must complete the exam on your own. Discussion and exchange the solutions between groups are not allowed. It is supposed that all groups are the same as the ones for laboratories and exercises. You must inform the teacher if you want to change the group members. • The grade/mark is evaluated based on the answers (or solutions) you write on sheets of paper that you submit at the end of the exam. It is important to note that each group only needs to complete and submit one exam report. Every page/sheet of your submission should have full name of two (or three) students and section numbers that address the corresponding tasks or questions (e.g. Task 1a, Task 2b, Question 2c, etc.). You should write the answers/solutions clearly and in easy way to understand. Illegible handwriting, unclear resulting plots, and loose sheets will not be graded. • You should be sure that your computers have enough battery/power for (at least) 5 hours. • Finally, it is necessary to note that you should write on your exam papers the most important part of Matlab code (in your opinions) to support your solutions or answers.

Conditions and the manner of completing each form of classes, including the rules of making retakes, as well as the conditions for admission to the exam

Students can only attend the final exam if they pass laboratory and exercise assignments, i.e. the "Average Lab & Exe" grade must be higher than or equal 3.0).

Method of determining the final grade

The final grade is based on grades obtained for exercises, laboratory assignments and the final exam, which are calculated as follows: • Exercises: 20% • Laboratory: 50% • Final exam: 30%. To avoid large errors while rounding grades, the "Average Lab & Exe" will be used for both laboratory and exercise grades. Average Lab & Exe = (Lab1 + Lab2 + Lab3 + Lab4 + Exe1 + Exe2)/6. Final Grade = 0.5*[(Lab1+Lab2+Lab3+Lab4)/4]+0.2*[(Exe1+Exe2)/2]+0.3*Exam. Students can only attend the final exam if they pass laboratory and exercise assignments, i.e. the "Average Lab & Exe" grade must be higher than or equal 3.0.

Manner and mode of making up for the backlog caused by a student justified absence from classes

- Students are provided with slides and notes from the lectures. The materials should be enough to recover the lack of knowledge due to the absence. - In the case of (justified) absence to laboratory classes, the student will be supported to repeat the missed work in another date.

Prerequisites and additional requirements

- Good background on basic automatic control theory – obtained form the subject "Control Theory Fundamentals" in Semester 3 – is a definite prerequisite for this module.
- Knowledge of basic linear algebra and complex number arithmetic is desirable.
- Prior experience with MATLAB/Simulink is required.

Rules of participation in given classes, indicating whether student presence at the lecture is obligatory

- Students are required to attend at least 70% of the lecture classes and 70% of the laboratory classes. - Attending auditorium classes is optional (i.e. not compulsory).

Literature

Obligatory

1. Roland S. Burns, "Advanced Control Engineering", Butterworth-Heinemann, 2001, ISBN 978-0-7506-5100-4.
2. Richard C. Dorf and Robert H. Bishop, "Modern Control Systems", 8th ed., Addison-Welley, Boston, MA, 1997, ISBN: 978-0-2013-0864-8.
3. Norman S. Nise, "Control Systems Engineering", 4th ed., John Wiley and Sons Inc., 2004, ISBN: 978-0-4714-4577-7.
4. MATLAB/Simulink, Control Systems Toolbox, and Fuzzy Logic Toolbox, http://www.mathworks.com/.

Optional

1. Students are provided with slides and notes from the lectures. Other relevant documents are provided during the course.

Scientific research and publications

Publications

1. Phong B. Dao, Theo J.A. de Vries, Job van Amerongen, “Safe-guarded agent design pattern for mechatronic systems,” Proceedings of the 5th IFAC Symposium on Mechatronic Systems (IFAC Proceedings), vol. 43, no. 18, pp. 345–354, 2010. Link: https://www.sciencedirect.com/science/article/pii/S1474667015375030
2. Phong B. Dao, “OROMACS: A design framework for multi-agent control system,” International Journal of Control, Automation and Systems, vol. 19, no. 5, pp. 1907–1919, 2021. Link: https://link.springer.com/article/10.1007/s12555-019-0772-3
3. Phong B. Dao, “Learning feedforward control using multiagent control approach for motion control systems,” Energies, vol. 14, no. 2, 420, 2021. Link: https://www.mdpi.com/1996-1073/14/2/420

Learning outcomes prescribed to a field of study

Code	Content
IMA1A_K02	awareness of the importance and understanding of the non-technical aspects and consequences of the activity of a mechatronic engineer, including its environmental impact and the resultant responsibility for decisions made
IMA1A_K04	awareness of the responsibility for own work and readiness to comply with the rules of team work and accepting responsibility for tasks performed collectively
IMA1A_K05	ability to correctly set priorities in meeting own or external objectives
IMA1A_K06	ability to think and act in an enterprising manner
IMA1A_K07	awareness of the social role of a graduate of technical studies, especially as regards the need to formulate and communicate to society, via the media, information and opinions regarding the achievements of mechatronics and other aspects of the activity of a mechatronic engineer; striving to convey such information and opinions in a commonly understandable manner
IMA1A_U01	ability to acquire information from literature, databases and other sources, integrate, select and interpret the information, draw conclusions, formulate and justify opinions
IMA1A_U02	ability to work individually or in team, to estimate the time needed to complete an assigned task; able to develop and complete a schedule of works and meet the deadlines
IMA1A_U03	ability to develop documentation related to the completion of an engineering task and prepare text discussing the results of the task
IMA1A_U04	ability to prepare and give a brief presentation of the results of the engineering task completed
IMA1A_U05	English language skills sufficient to communicate and read data sheets, application notes, manuals of the components of mechatronic systems, IT tools and other similar documents
IMA1A_U07	ability to use methods and mathematical models and computer simulations to analyse and assess the operation of mechatronic equipment and systems
IMA1A_U08	ability to use properly selected programming environments, simulators and computer aided design tools for the simulation, design and verification of components of mechatronic devices and systems
IMA1A_U10	ability to formulate the specification of simple mechatronic systems at the level of functions being performed
IMA1A_U11	ability to perform critical analysis of the performance and assess the existing technical solutions in mechatronic devices and systems
IMA1A_U16	ability to perform a synthesis, stability analysis and simulation testing of a continuous or a discrete control algorithm for a given single- or multi-dimensional, linear or non-linear object
IMA1A_U20	ability to evaluate the usefulness of routine methods and tools for solving simple engineering tasks typical for mechatronics and select and apply proper methods and tools
IMA1A_W01	extensive knowledge of mathematics, including algebra, analysis, probabilistic and elements of discrete and applied mathematics, including numerical and mathematical methods, necessary for formulating and solving complex problems in mechatronics
IMA1A_W04	elementary knowledge of electronics and electrical engineering
IMA1A_W08	well-ordered and theory-based knowledge of technical mechanics necessary for formulating and solving problems in mechatronics
IMA1A_W09	well-ordered and theory-based knowledge of basic automatics and control theory
IMA1A_W10	well-ordered knowledge of microprocessor systems, basics of IT science, programming methods and techniques
IMA1A_W12	knowledge and understanding of the methodology of designing mechatronic devices and methods and techniques used for the design, including the artificial intelligence method; knowledge of computer tools for the design and simulation of mechatronic devices