Technische Universität Dortmund
Fakultät für Elektrotechnik und Informationstechnik

Modulhandbuch
(Module Book)
für den Masterstudiengang
Automation und Robotics
PO 2019

Entwurf

Aktualisierte Version gemäß Beschluss des
Fakultätsrates vom XX.XX.2020

Versionsinformationen

V 1.0: Vom Fakultätsrat der Fakultät für Elektrotechnik und Informationstechnik am 30.01.2019 beschlossene Version des Modulhandbuchs

Änderungen der Version vom 20.09.2019 gegenüber der Basisversion vom 30.01.2019:

- Wegfall des Moduls AR-224
- Wegfall des Moduls AR-313 „Multivariable Control"
- Aufnahme des Moduls AR-315: „Real-Time Operating Systems De-sign and Implementation"
- Aufnahme des Moduls AR-316: „Online Problems"
- Aufnahme des Moduls AR-317: „Human-Centered Robotics"

Änderungen der Version vom 20.09.2019 gegenüber der Basisversion vom 30.01.2019:

- Neuaufnahme des Moduls AR-226 „Robot und Interface Mechanisms"
- Neuaufnahme des Moduls AR-227 „Hardware Software Codesign"
- Neuaufnahme des Moduls AR-228 „Distributed and Networked Control"
- Neuaufnahme des Moduls AR-229 „Single-Loop and Multi-Loop Controller Design
- Neuaufnahme des Moduls AR-318 „Nonlinear Model Predictive Control – Theory and Applications"

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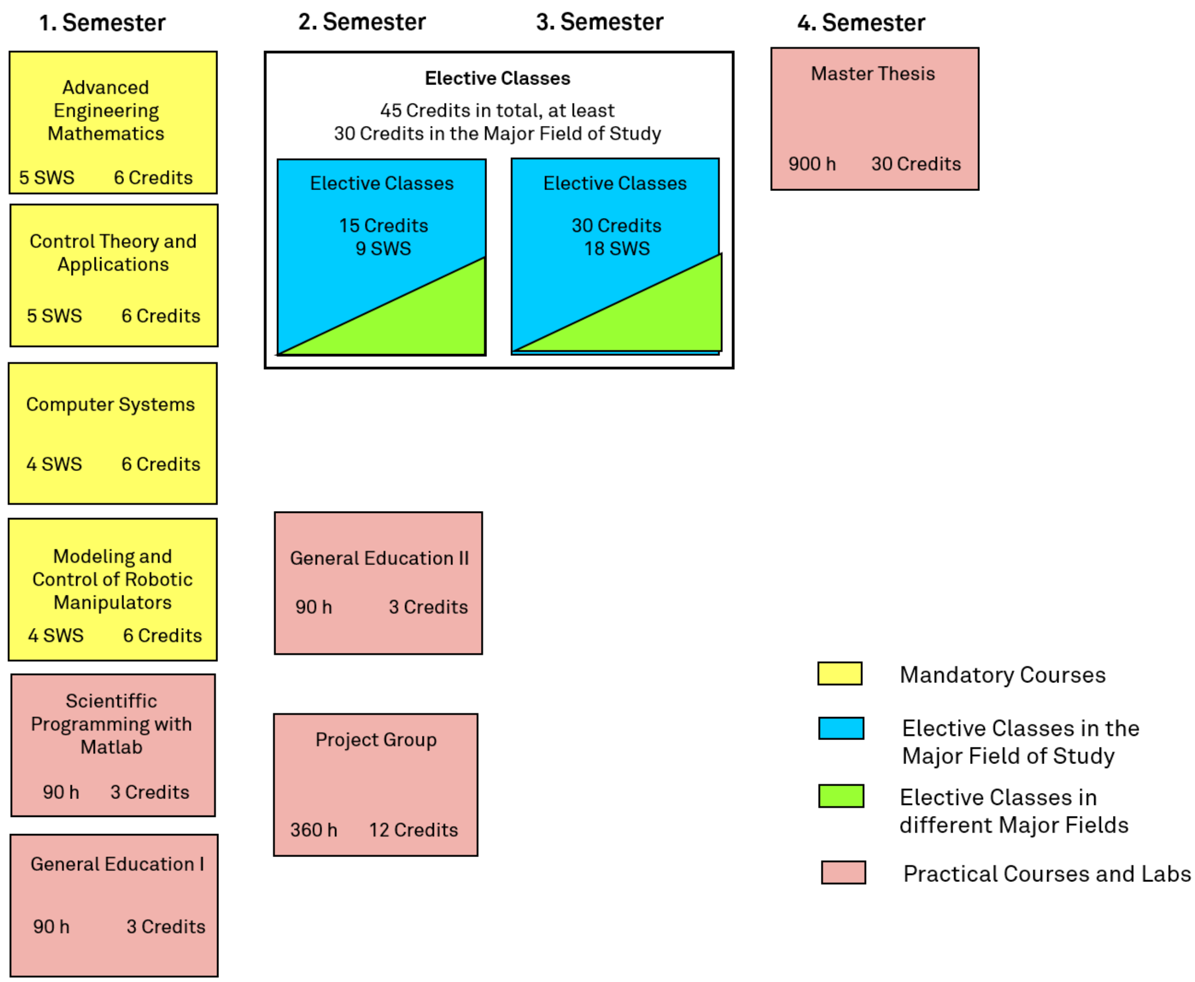
Studienverlaufsplan



Zwei Wahlpflichtmodule mit demselben Schwerpunkt können mit einer gemeinsamen Modulprüfung abgeschlossen werden. Die Kombinationen werden mit dem/ der jeweiligen Modulverantwortlichen abgesprochen. Es können pro Modulprüfung jedoch maximal 10 Leistungspunkte erworben werden.

1. Semester

Advanced Engineering Mathematics — AR-101

Rota	Duration	Semester	SWS	Credit Points	Workload
annually WS	1 Semester	1st (Semester)	5 SWS	6	180 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Advanced Engineering Mathematics (AEM)	Lecture/ 3 SWS	35 h	85 h	4
b) Advanced Engineering Mathematics (AEM)	Tutorial/ 2 SWS	25 h	35 h	2

2 Language

English

3 Content

The subjects are chosen from

1. <u>Linear Algebra:</u> Vector spaces, matrices and equation systems, linear maps, Jordan-, LU-, QR-, and singular value decomposition, numerical aspects.
2. <u>Differential Equation:</u> Linear systems, differential equations with constant coefficients.
3. Laplace-Transform and Fourier Series
4. <u>Differential Calculus with several variables:</u> Derivatives, inverse and implicit functions, Taylor expansion and extreme values.
5. <u>Stability of Differential Equations:</u> Theorems of Ljapunov and Poincaré-Ljapunov.
6. <u>Variational Calculus</u>

Literature:

- Bajpai, Avinash C. , Mathematics for engineers and scientists
- Meyer, R.M., Essential mathematics for applied fields
- Lancaster, P., Tismenetsky, M., The theory of matrices
- Lang, S., Linear algebra
- Slides

4 Competencies

The course gives an introduction to fundamental mathematical techniques used in almost every course. Attention is given to the underlying mathematical structure.

5 Examination Requirements

The final exam will be a written (2 hours) exam.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

8 Allocation to Curriculum:

Mandatory Course
Program: Automation & Robotics

9 Responsibility/ Lecturer

Dean of the Mathematics faculty/ Lecturers of the Mathematics faculty

Control Theory and Applications					AR-102
Rota annually WS	**Duration** 1 Semester	**Semester** 1st (Semester)	**SWS** 5 SWS	**Credit Points** 6	**Workload** 180 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Control Theory and Applications (CTA)	Lecture / 3 SWS	35 h	85 h	4
b) Control Theory and Applications (CTA)	Tutorial / 2 SWS	25h	35 h	2

2 Language

English

3 Content

- Modeling of dynamic systems: First principles models, state space representation, DAE systems, classes of systems, models, and signals, linearity and causality, steady states, operability, singular value decomposition, stability, linearization.
- Linear state space theory: Autonomous behavior, eigenvalues, eigenvectors, Jordan form, controllability and pole assignment, LQ-optimal control, observability, observers, observer-based control, Kalman decomposition.
- Laplace transform and transfer matrices: Introduction to the Laplace transform, transfer functions, poles, zeros, minimal realization, zeros of multivariable systems, frequency response, input-output stability.
- Design of single-loop controllers: Internal stability, performance specification, classical SISO controller design, robust stability and performance, performance limitations
- Discrete-time and sampled data systems: z-transform, z-transform of sampled data systems, stability, dead-beat control, w-transform

Literature:

- Handouts
- S. Skogestad, Postlethwaite: Multivariable Feedback Control, Wiley, 1996.
- K. Zhou, J.Doyle: Essentials of Robust Control, Prentice Hall, 1998.

4 Competencies

This course provides the students with a solid background in control theory which is a prerequisite to solve automation problems in robotics as well as in production processes of all kinds.

5 Examination Requirements

The final exam will be a written (2 hours) exam. In addition, there will be a written midterm exam (1.5 hours).

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

8 Allocation to Curriculum:

Mandatory Course
Program: Automation & Robotics

9 Responsibility/ Lecturer

Prof. Dr. S. Engell/ Prof. Dr. S. Engell

Computer Systems					AR-103
Rota annually WS	**Duration** 1 Semester	**Semester** 1st (Semester)	**SWS** 4 SWS	**Credit Points** 6	**Workload** 180 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Computer Systems (CS)	Lecture/ 3 SWS	35 h	85 h	4
b) Computer Systems (CS)	Tutorial/ 1 SWS	15 h	45 h	2

2 Language

English

3 Content

1. Microprocessors: Processor performance, instruction set, compilers, pipelining, and superscalar architectures
2. Storage Technology: SRAM, DRAM, ROM, magnetic recording, optical recording
3. Data Communication: Bus systems, Ethernet, TCP/IP
4. Memory Hierarchy: Caches, virtual memory, RAID systems

Literature:

- General, Communication within Computer Systems: John L. Hennessy, David A. Patterson, "Computer Architecture, a Quantitative Approach", 3rd Edition, Morgan Kaufmann, 2002
- Semiconductor memory: Betty Prince, "High Performance Memories", Wiley, 1999
- Optical Storage: Alan Marchant, "Optical Recording", Addison Wesley, 1999
- Communication between Computer Systems: Andrew S. Tanenbaum, "Computer Networks", Prentice Hall, 3rd edition 1996, ISBN 0133499456
- Larry L. Peterson, Bruce S. Davie, "Computer Networks, A Systems Approach", Morgan Kaufmann, 2nd ed. 1999

4 Competencies

By attending this course, students learn the architecture and the components of modern computer systems. This knowledge is directly required for advanced courses on distributed systems and communication systems. As computers are vital components of most robots and complex process automation systems, a basic understanding of computer systems is necessary for most practical work in this area, like project groups and lab courses.

5 Examination Requirements

All students are required to successfully complete 2 out of 4 special assignments in order to be admitted to the final exam. The final exam is a written test (3 hours). The grade is solely determined by the final exam.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

8 Allocation to Curriculum:

Mandatory Course

Program: Automation & Robotics

9 Responsibility/ Lecturer

Jun.-Prof. Dr. Fang-Jing Wu/ Jun.-Prof. Dr.-Fang-Jing Wu

Modeling and Control of Robotic Manipulators					AR-106
Rota annually WS	**Duration** 1 Semester	**Semester** 1st (Semester)	**SWS** 4 SWS	**Credit Points** 6	**Workload** 180 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Modeling and Control of Robotic Manipulators (MCRM)	Lecture/ 2 SWS	25 h	65 h	3
b) Modeling and Control of Robotic Manipulators (MCRM)	Tutorial/ 1 SWS	15 h	45 h	2
c) Modeling and Control of Robotic Manipulators (MCRM)	Lab	10	20	1

2 Language

English

3 Content

1. Spatial Representations
2. Direct Kinematics
3. Differential Kinematics
4. Dynamics
5. Actuators and Sensors
6. Motion Control
7. Interaction Control
8. Robotics System Toolbox and ROS

Literature:

- Sciavicco, Siciliano: Modelling and Control of Robotic Manipulators

4 Competencies

This course provides the students with a profound background of modelling, planning and control of robotic manipulators.
The students acquire practical experience in robot kinematics, dynamics and motion control under ROS/Matlab.

5 Examination Requirements

written exam (3 hours)

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

8 Allocation to Curriculum:

Mandatory Course
Program: Automation & Robotics)

9 Responsibility/ Lecturer

apl. Prof. Dr. F. Hoffmann / apl. Prof. Dr. F. Hoffmann

Scientific Programming with Matlab in Engineering					AR-105
Rota annually WS	**Duration** 1 Semester	**Semester** 1st (Semester)	**SWS** 3 SWS	**Credit Points** 3	**Workload** 90 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Scientific Programming with Matlab in Engineering (SPM)	Lab/ 3 SWS	35 h	55 h	3
2	**Language** English				
3	**Content** 1. Matlab Basics, Programming, Visualization 2. Symbolic Computing 3. Statistics 4. Numerical Optimisation 5. Control System Design 6. Simulink 7. Robotics **Literature:** Matlab documentation				
4	**Competencies** The course qualifies the students to solve scientific programming and engineering problems with Matlab. The students acquire deeper knowledge in the design and application of control systems and robotics.				
5	**Examination Requirements** Successful completion of 75% of programming assignments and Successful completion of 50% of quizzes The course grading is pass or fail.				
6	**Formality of Examination** ☐ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)**				
8	**Allocation to Curriculum:** Mandatory Course Program: Automation & Robotics				
9	**Responsibility/ Lecturer** *apl. Prof. Dr. F. Hoffmann* / apl. Prof. Dr. F. Hoffmann				

General Education I					AR-371
Rota WS	**Duration** 1 Semester	**Semester** 1st Semester	**SWS** 4 SWS	**Credit Points** 3	**Workload** 90 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	1. Language Class (German as foreign language)	Seminar/ 4 SWS	45 h	45 h	3
	2. Foreign Language Class (Native speakers in German)	Seminar/ 4 SWS	45 h	45 h	3
	3. Presentation Class	Seminar/ 4 SWS	45 h	45 h	3

2 Language: English/ German

3 Content

Course 1 or 2

Students acquire capabilities to communicate private information in past and present, to name and ask for professions or study subjects and to query simple information on job offers. Furthermore skills to express commands or giving guidance on an entry level, to make appointments or communicate emergencies, e.g. being sick, via phone, are trained. Further skill to be trained are listed but not limited to

- understand and phrase phone messages
- ask for explanations and express polite support requests or instructions
- query or explain a route to a target
- read or write invitations and express good wishes
- name pieces of clothing and body parts

Course 3

Students acquire and apply methods for self– and time–organization, to guide negotiations and presentations, organization of workflows, to handle information plethora, self and object presentation.

4 Competencies

Successful completion of this module will grant knowledge of a non–native language and will have gained or enhanced either cultural knowledge or presentation skills for the chosen target nation.
Besides enhancing the general scope of education other key competences are supposed to be enabled. The necessity to freely choose classes for this subject is supposed to strengthen unsupervised learning skills and self–motivation related to academic studies.

5 Examination Requirements

3 Credits will be rewarded for either taking a class acknowledged for 1 or 2 or 3. Each class has to be passed by a final examination. Modalities of examinations are subject to the responsible lecturer. Passing the examination and assignment of credits shall be marked on a course–passing certificate.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

Each student who chooses a language class for the General Education subject has to opt for a language other than his or her mother language.

8 Allocation to Curriculum:

Program: Automation & Robotics

9 Responsibility/ Lecturer

Dean of the faculty of Electrical Engineering and Information Technology

2. Semester

Application of Robots					AR-201
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 2 SWS	**Credit Points** 3	**Workload** 90 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Application of Robots (AoR) (APPL)	Lecture/ 2 SWS	25 h	65 h	3
2	**Language** English				
3	**Content** The following topics are discussed in detail: • Introduction to the term "robot system" • Components of industrial robot systems: robots, effectors, feeding systems, clamping devices, control and communication systems, safety systems and other peripheral devices • Interaction of the individual components • Robot applications in production and manufacturing systems • Robot applications for assembly tasks **Literature:** • William R. Tanner: Industrial Robots: Applications • Phillip John McKerrow: Introduction to Robotics				
4	**Competencies** This lecture treats applications of robotics in the industrial environment. The first part of the lecture focuses on robot systems. On the basis of practical examples the components of industrial robot systems and their interaction in a production process are systematically analyzed and described. Based on this theoretical background an overview of state of the art applications is given, in order to deepen the subjects and to establish the relationship between theory and practice. In addition, actual research work is presented.				
5	**Examination Requirements** All students are required to solve four assignment problems. The final exam will be an oral (30 minutes) or written (2 hour) exam, depending on the number of participants.				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)**				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Robotics				
9	**Responsibility/ Lecturer** *Prof. Dr. J. Bickendorf/* Prof. Dr. J. Bickendorf				

<table>
<tr><td colspan="5">Scheduling Problems and Solutions</td><td>AR-202</td></tr>
<tr><td>Rota
bi-annually SS</td><td>Duration
1 Semester</td><td>Semester
2nd (Semester)</td><td>SWS
7 SWS</td><td>Credit Points
10</td><td>Workload
300 h</td></tr>
</table>

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Scheduling Problems and Solutions (SPaS)	Lecture/ 4 SWS	45h	135 h	6
b) Scheduling Problems and Solutions (SPaS)	Tutorial/ 2 SWS	25 h	95 h	4
c) Scheduling Problems and Solutions (SPaS)	Lab/ 1 SWS	15 h		

2 Language

English

3 Content

1. Single Machine Models: Classification, complexity, total weighted completion time, maximum lateness and multiple objectives
2. Parallel Machine Models: Makespan, total completion time, preemption
3. Shop Systems: Flow shop, flexible flow shop, job shop, open shop
4. Online Scheduling: Competitive factors, non clairvoyant scheduling
5. Scheduling in Practice: Computer intelligence, Integer linear programming

Literature:

- M. Pinedo: Scheduling - Theory, Algorithms and Systems, 4th edition, Springer 2012
- Yves Robert, Frédéric Vivien (ed.): Introduction to Scheduling, CRC Press, 2010

4 Competencies

The students know the classification of scheduling problems as well as the application of practical algorithms, heuristics, and methods in order to solve these combinatorial resource allocation tasks. They can evaluate the efficiency of classical solution methods and will be able to develop new solution approaches for complex scheduling problems based on their acquired knowledge.

5 Examination Requirements

Dependent on the number of participants the final exam is takes place as oral (40 min) or written exam (2h). The students must successfully participate in the lab course as preparation for the exam.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems

9 Responsibility/ Lecturer

Prof. Dr. Uwe Schwiegelshohn/ Prof. Dr. Uwe Schwiegelshohn

Process Automation | AR-205

Rota	Duration	Semester	SWS	Credit Points	Workload
annually SS	1 Semester	2nd (Semester)	8 SWS	10	300 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Logic Control (LC)	Lecture / 2 SWS	25 h	65 h	3
b) Logic Control (LC)	Tutorial / 2 SWS	25 h	65 h	3
c) Process Control Lab	Lab / 4 SWS	45 h	75 h	4

2 Language: English

3 Content

(a, b) Logic controllers are widely used to supervise the safe operation of equipment, and to enforce desired operating sequences. In many applications, such controllers are realized by Programmable Logic Controllers (PLCs) or Distributed Control Systems (DCSs). The course covers the underlying mathematical models and notions, teaches basic design concepts for logic control, and introduces into the programming of PLCs. In the tutorials, the students design, implement, and test logic controllers for simple examples. The students have to perform a logic controller programming task as a home assignment.

1. Introduction: motivation and application examples for logic control
2. Mathematical foundations: Boolean algebra and functions
3. Hardware realization of logic controllers
4. Fundamentals of PLC programming: PLC operating systems and standard functions
5. Programming languages according to the international standard IEC 61131-3 (including function block diagrams, ladder diagrams, instruction list and structured text programs, and the specification of sequential controls by sequential function charts)

(c) A Process Control Lab consisting of six practical lab experiments (DYN 2, DYN 3, DYN 5, DYN 6, DYN 10, DYN 11) and three computer experiments (DYN 22 a, b, DYN 26) (see appendix A).

Literature:

- R.W.Lewis: Programming Industrial Control Systems using IEC6113-3. IEE Control Engineering Series, No, 5, IEE, London, 1995
- Karl-Heinz John, M. Tiegelkamp: IEC 61131-3: programming industrial automation systems. Springer, ISBN: 3-540-67752-6, Berlin, 2001
- C. G. Cassandras, S. Lafortune: Introduction to Discrete Event Systems. Kluwer Academic Publishers, 1999
- J. E. Hopcroft, J. D. Ullman: Introductions to Automata Theory, Languages, and Computation. Addison Wesley, 2000

4 Competencies

In this course, the students learn the importance of logic control and the state of the art of the technology used to implement such controllers. They can analyze and formalize the tasks of a logic controller and can formally specify its behavior. They are able to implement simple logic controllers and to apply modern techniques to their analysis. They can evaluate the complexity of a logic control task. The Process Control Laboratory allows the students to apply control theory from this and other courses to realistic example problems.

5 Examination Requirements

The final exam will be an oral (30 minutes) or written (2 hour) exam, depending on the number of participants (form will be announced in the second week of the course). In addition, there will be a graded home assignment. The requirements for the laboratory are described in appendix A.

6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade
7	**Module Requirements (Prerequisites)** The lab course builds upon the course Control Theory and Applications which is compulsory in the first semester.
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Process Automation As major field of study in Process Automation, this course is mandatory.
9	**Responsibility/ Lecturer** *Prof. Dr. S. Engell/* Prof. Dr. S. Engell

Data-Based Dynamic Modeling | AR-206

Rota	Duration	Semester	SWS	Credit Points	Workload
annually SS	1 Term	2nd (Semester)	2 SWS	3	90 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Data-Based Dynamic Modeling (DDM)	Lecture/ 1 SWS	15 h	45 h	2
b) Data-Based Dynamic Modeling (DDM)	Tutorial/ 1 SWS	15 h	15 h	1

2 Language

English

3 Content

1. Identification of simple models from step responses.
2. Parameter identification: Basic idea, mathematical description of sampled systems, ARX, ARMAX and OE estimation.
3. Modeling using nonlinear black box models (perceptron neural nets, radial-basis-function nets), training, dynamic models, quality of neural net models.
4. Model errors: Sources of errors, limits of model accuracy, model accuracy and controller performance.

The course takes place in the second half of the semester.

Literature:

- Slides
- Handouts

4 Competencies

The students can identify the dominant dynamics of a process from step responses and can apply modern methods and algorithms to identify the parameters of linear process models from measured data. They know the structure of nonlinear black box models and can judge the quality and the limitations of data-based models.

5 Examination Requirements

The final exam will be an oral (30 minutes) or written (2 hours) exam, depending on the number of participants (form will be announced in the second week of course). In addition, there will be a graded homework.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

Basic knowledge of dynamic systems as e.g. provided by the course Control Theory and Applications.

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Process Automation Robotics, Cognitive Systems

9 Responsibility/ Lecturer

Prof. Dr. S. Engell/ Prof. Dr. S. Engell

Process Optimization					AR-207
Rota annually SS	**Duration** 1 Term	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 4	**Workload** 120 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Process Optimization (PO)	Lecture/ 1 SWS	15 h	45 h	2
	b) Process Optimization (PO)	Tutorial/ 1 SWS	15 h	15 h	1
	c) Process Optimization (PO)	Lab / 1 SWS	15 h	15h	1

2 Language

English

3 Content

The course gives an overview of state-of-the-art process optimization techniques and of their application. The following topics are dealt with:

- Scalar and multivariable optimization
- Linear and nonlinear programming, direct and indirect methods
- Constrained Optimization
- Evolutionary Algorithms
- Nonlinear Programming with Equality and Inequality Constraints

The course takes place in the second half of the semester.

4 Competencies

The students acquire an in-depth knowledge of methods and technologies for the improvement of chemical and biochemical production processes by optimization. The students acquire a comprehensive overview of the industrial practice in this area.

5 Examination Requirements

The final exam will be an oral (20 minutes) or written (1.5 hours) exam, depending on the number of participants (form will be announced in the second week of the course). In addition, the lab must be passed.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

This module is mutually exclusive with the module “Process Performance Optimization”. By receiving credit points for the module “Process Optimization” you cannot receive credit points the module “Process Performance Optimization”.

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Process Automation Robotics, Cognitive Systems

9 Responsibility/ Lecturer

Prof. Dr. S. Engell/ Prof. Dr. S. Engell

Computer Vision | AR-210

two-year Rota	Duration	Semester	SWS	Credit Points	Workload
SS	1 Semester	2nd (Semester)	4 SWS	6	180 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Computer Vision (CV)	Lecture/ 2 SWS	25 h	95 h	4
b) Computer Vision (CV)	Tutorial/ 2 SWS	25 h	35 h	2

2 Language: English

3 Content

For the majority of living beeings vision is the most important perception mechanism for orienting themselves in the environment. Therefore, there exists a multitude of attempts to recreate this capability in artificial systems. In contrast to image processing techniques found in industrial applications the aim of such advanced systems for machine vision is to obtain a task-oriented interpretation of a complex scene with as few restrictions as possible concerning the context and the recording conditions.

In this lecture advanced techniques of machine vision are covered which to some extent are inspired by cognitive processes known from human visual perception. First, important aspects of imaging processes are introduced with an emphasis on the perception of colors. Afterwards, methods for the computation of local feature representations (e.g. texture, depth, or motion) and for the extraction of image primitives (e.g. regions, contours and keypoints) are presented. Finally, the lecture focusses on visual perception processes at the boundary between image processing and scene interpretation. Several appearance based object recognition techniques will be covered, e.g., Bag-of-Features approaches, Eigenimages, and deep Convolutional Neural Networks (CNNs) which define the state-of-the art for many current computer vision problems.

The accompanying tutorials will give students the opportunity to deepen their knowledge of the theoretical concepts presented in the lecture by working on relevant practical problems.

Literature:

- Szeliski, Richard: Computer Vision, Springer, 2010.
- Gonzalez, Rafael C.; Woods, Richard E.: Digital Image Processing, Pearson, 4nd Ed., 2017.
- Forsyth, David A.; Ponce, Jean: Computer Vision - A Modern Approach, Prentice Hall, 2003.

4 Competencies In this module students will be made familiar with solutions for advanced problems in the field of machine vision. A fundamental understanding of the principles underlying visual perception systems will enable participants to apply such techniques by themselves in innovative application scenarios - as, e.g., robotics and human-machine interaction – and to assess their strengths and limitations.

5 Examination Requirements

The final exam will be an oral (30-45 minutes) exam.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems

9 Responsibility/ Lecturer

Prof. Dr. G. Fink/ Prof. Dr. G. Fink

3 D Computer Vision					AR-213
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) 3D Computer Vision	Lecture/ 2 SWS	25 h	65 h	3
	b) 3D Computer Vision	Tutorial/ 1 SWS	15 h	45 h	2

2 Language

English

3 Content

1. Introduction to projective geometry
2. Linear and nonlinear approaches to the calibration of camera systems
3. 3D reconstruction based on photogrammetric methods, especially bundle adjustment
4. Pattern classification methods for establishing point correspondences between images
5. Model-based 3D pose estimation
6. 3D reconstruction based on the point spread function (depth from focus/defocus)
7. 3D reconstruction of surfaces based on their physical reflectance properties (photoclinometry, shape from shading/polarisation)
8. Technical and scientific applications

Literature:

- Horn: Robot Vision
- Klette, Koschan, Schlüns: Computer Vision: Three-Dimensional Data from Images;
- Hartley/Zisserman: Multiple Viewpoint Geometry

4 Competencies

The students obtain the ability to understand, develop, and implement 3D computer vision methods and apply them to practical technical or scientific problems.

5 Examination Requirements

The final exam will be an oral or written exam (form will be announced in the third week of the course).
Each student has to participate in 5 practical programming lectures successfully.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

Good knowledge in linear algebra as well as linear and nonlinear optimization.

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems

Program: Electrical Engineering und Information Technology (ETIT-233)

9 Responsibility/ Lecturer

Prof. Dr. C. Wöhler/ Prof. Dr. C.Wöhler

Aspects of Mathematical Modeling					AR-214
Rota annually WS or SS	**Duration** 1 Semester	**Semester** 2^{nd}/3rd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Aspects of Mathematical Modeling (AMM)	Lecture/ 2 SWS	25 h	65 h	3
	b) Aspects of Mathematical Modeling (AMM)	Tutorial/ 1 SWS	15 h	45 h	2
2	**Language:** English				

3 Content

Different directions of mathematical modeling techniques are introduced that build on the course Advanced Engineering Mathematics and assume a solid background in mathematics. Among the subjects are the following:

1. Optimization: Theoretical and practical aspects of optimization problems, formulation, optimality conditions, linear programming, discrete optimization.
2. Applied partial differential equations: Prototypes, representation formulae, qualitative and quantitative behavior, conservation laws, elliptic, parabolic and hyperbolic equations, convection-diffusion-reaction systems.
3. Continuum mechanics: Inertia and momentum, equations of motion, external forces, conservation laws, deformations.
4. Modeling: Modeling with differential equations: Autonomous systems, linearization, phase plane analysis, non-dimensionalization, network dynamics, stability, bifurcations. Stochastic modeling: statistical inference, stochastic processes.

Literature:

References will be given in the courses.

4 Competencies

This course offers an introduction to different fundamental techniques of mathematical modeling and analysis that are useful for the dynamics and control of robotic devices. Tools that allow for the description and control of movement and the interaction with the environment are introduced. The ability to create and use models to estimate qualitatively and quantitatively the behavior of dynamic systems will be trained.

5 Examination Requirements

The final exam will be an oral (20 minutes) or written (1.5 hours) exam, depending on the number of participants (form will be announced in the second week of the course).

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

Course: “Advanced Engineering Mathematics”

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Robotics, Process Automation, Cognitive Systems

9 Responsibility/ Lecturer

Dean of the Mathematics faculty / Lecturers of the Mathematics faculty

<table>
<tr><td colspan="6">Cyber-Physical System Fundamentals</td><td>AR-215</td></tr>
<tr><td colspan="2">Rota
annually SS</td><td>Duration
1 Semester</td><td>Semester
2nd (Semester)</td><td>SWS
4 SWS</td><td>Credit Points
6</td><td>Workload
180 h</td></tr>
<tr><td rowspan="4">1</td><td colspan="6">Modul Structure</td></tr>
<tr><td colspan="2">Course (Abbreviation)</td><td>Type/ SWS</td><td>Presence</td><td>Self Study</td><td>Credit Points</td></tr>
<tr><td colspan="2">a) Cyber-Physical System Fundamentals (CPSF)</td><td>Lecture/ 4 SWS</td><td>45 h</td><td>75 h</td><td>4</td></tr>
<tr><td colspan="2">b) Cyber-Physical System Fundamentals (CPSF)</td><td>Lab</td><td colspan="2">60 h</td><td>2</td></tr>
<tr><td>2</td><td colspan="6">Language: English</td></tr>
<tr><td>3</td><td colspan="6">Content:
The course is based on the presenter’s book on the subject and includes the following topics:
1. Introduction: Definition of terms, scope of the course
2. Specification and modeling: models of computation, communication models, finite state machines, data flow, discrete event models, von-Neumann-models, expressiveness of models
3. CPS hardware: hardware-in-the-loop, sampling and A/D-conversion, processing, field-programmable gate arrays (FPGAs), communication hardware, D/A-conversion, sampling theorem, output
4. Standard software: embedded operating systems, real-time operating systems, priority inversion, middleware
5. Evaluation and validation: objective functions, Pareto-optimality, worst-case execution time, energy consumption, reliability, real-time calculus, verification
6. Mapping of applications to execution platforms: standard optimization techniques, real-time scheduling, rate monotonic scheduling, earliest deadline first scheduling, hardware/software partitioning, mapping of applications to heterogeneous multiprocessors
7. Selected optimizations.
Literature:
• Peter Marwedel: Embedded System Design – Cyber Physical System Fundamentals, Springer, 2010
• Lego Mindstorm NXT Technical documentation
• Technical documentation fort he used finite state machine design tool (StateMate or similar)</td></tr>
<tr><td>4</td><td colspan="6">Competencies
Students successfully finishing the course should be able to
• Understand how cyber-physical (CPS) hardware interacts with CPS software and use this knowledge to design CPS software,
• Select models of computation and programming languages that are appropriate for a given design problem,
• Select an appropriate scheduling technique for embedded systems, Apply hardware/ software design techniques in order to optimize the systems which they are supposed to design.</td></tr>
<tr><td>5</td><td colspan="6">Examination Requirements
The students have to pass both the lab and the finals.</td></tr>
<tr><td>6</td><td colspan="6">Formality of Examination
☒ Module Finals ☐ Accumulated Grade</td></tr>
<tr><td>7</td><td colspan="6">Module Requirements (Prerequisites)
Basic knowledge in programming as well as finite-state machines.</td></tr>
</table>

8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Robotics, Process Automation, Cognitive Systems,
9	**Responsibility/ Lecturer** *Prof. Dr. J. Chen/* Prof. Dr. J. Chen

Logic Control					AR-220
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 4 SWS	**Credit Points** 6	**Workload** 180 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	d) Logic Control (LC)	Lecture / 2 SWS	25 h	65 h	3
	e) Logic Control (LC)	Tutorial / 2 SWS	25 h	65 h	3

2 **Language**

English

3 **Content**

Logic controllers are widely used to supervise the safe operation of equipment, and to enforce desired operating sequences. In many applications, such controllers are realized by Programmable Logic Controllers (PLCs) or Distributed Control Systems (DCSs). The course covers the underlying mathematical models and notions, teaches basic design concepts for logic control, and introduces into the programming of PLCs. In the tutorials, the students design, implement, and test logic controllers for simple examples. The students have to perform a logic controller programming task as a home assignment.

1. Introduction: motivation and application examples for logic control
2. Mathematical foundations: Boolean algebra and functions
3. Hardware realization of logic controllers
4. Fundamentals of PLC programming: PLC operating systems and standard functions
5. Programming languages according to the international standard IEC 61131-3 (including function block diagrams, ladder diagrams, instruction list and structured text programs, and the specification of sequential controls by sequential function charts)

Literature:

- R.W.Lewis: Programming Industrial Control Systems using IEC6113-3. IEE Control Engineering Series, No, 5, IEE, London, 1995
- Karl-Heinz John, M. Tiegelkamp: IEC 61131-3: programming industrial automation systems. Springer, ISBN: 3-540-67752-6, Berlin, 2001
- C. G. Cassandras, S. Lafortune: Introduction to Discrete Event Systems. Kluwer Academic Publishers, 1999
- J. E. Hopcroft, J. D. Ullman: Introductions to Automata Theory, Languages, and Computation. Addison Wesley, 2000

4 **Competencies**

In this course, the students learn the importance of logic control and the state of the art of the technology used to implement such controllers. They can analyze and formalize the tasks of a logic controller and can formally specify its behavior. They are able to implement simple logic controllers and to apply modern techniques to their analysis. They can evaluate the complexity of a logic control task.

5 **Examination Requirements**

The final exam will be an oral (30 minutes) or written (2 hour) exam, depending on the number of participants (form will be announced in the second week of the course). In addition, there will be a graded home assignment.

6 **Formality of Examination**

☒ Module Finals ☐ Accumulated Grade

7 **Module Requirements (Prerequisites)**

	-
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems
9	**Responsibility/ Lecturer** *Prof. Dr. S. Engell/* Prof. Dr. S. Engell

Dynamic Models					AR-221
Rota annually SS	**Duration** 1 Term	**Semester** 2nd (Semester)	**SWS** 2 SWS	**Credit Points** 3	**Workload** 90 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
c) Dynamic Models (DM)	Lecture/ 1 SWS	15 h	45 h	2
d) Dynamic Models (DM)	Tutorial/ 1 SWS	15 h	15 h	1

2 Language

English

3 Content

- Modeling and simulation of dynamic distributed parameter systems: fundamental equations, initial and boundary conditions, solution of partial differential equation systems by spatial discretization and orthogonal collocation.
- Differential algebraic equation systems: origin of DAE systems, index of a DAE system, numerical solution.
- Model simplification.

The course takes place in the first half of the semester.

Literature

- Slides
- Handouts

4 Competencies

The students can formulate PDE models of processing systems and can discretize the models and apply suitable numerical algorithms for their solution. They know the specific problems related to the solution of DAE models and can reduce dynamic models tailored to the purpose of the model.

5 Examination Requirements

The final exam will be an oral (30 minutes) or written (2 hours) exam, depending on the number of participants (form will be announced in the second week of course). In addition, there will be a graded homework.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

Basic knowledge of dynamic systems as e.g. provided by the course Control Theory and Applications.

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Process Automation, Robotics, Cognitive Systems

9 Responsibility/ Lecturer

Prof. Dr. S. Engell/ Prof. Dr. S. Engell

Logistics of Chemical Production Processes — AR-222

Rota	Duration	Semester	SWS	Credit Points	Workload
annually SS	1 Semester	2nd (Semester)	2 SWS	3	90 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Logistics of Chemical Production Processes	Lecture / 1 SWS	15 h	45 h	2
b) Logistics of Chemical Production Processes	Tutorial / 1 SWS	15 h	15 h	1

2 Language

English

3 Content

The students obtain an overview of supply chain management and planning and scheduling problems in the chemical industry and of techniques and tools for modeling, simulation and optimization. These include discrete event simulation, equation-based modeling, mixed-integer linear programming, heuristic optimization methods and modeling and optimization using timed automata.

Literature:

- Handouts
- Slides

4 Competencies

The students will be enabled to identify logistic problems, to select suitable tools and techniques for simulation and optimization and to apply them to real-world problems.

5 Examination Requirements

The final exam will be an oral (20 minutes) or written (1.5 hours) exam, depending on the number of participants (form will be announced in the second week of the course). In addition, active participation and collaboration in 3 computer exercises is required.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

-

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Process Automation

9 Responsibility/ Lecturer

Prof. Dr. S. Engell/ Prof. Dr. S. Engell

Statistics for Researchers in Engineering Sciences					AR-223
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Statistics for Researchers in Engineering Sciences (STAT)	Lecture/ 2 SWS	25 h	65 h	3
	b) Statistics for Researchers in Engineering Sciences (STAT)	Tutorial/ 1 SWS	15 h	45 h	2
2	**Language** English				
3	**Content** 1. Empirical distributions and explanatory data analysis: frequency tables, bar charts, histograms, distribution characteristics 2. Probability theory: conditional probability, independence 3. Random variables and their distributions: discrete distributions (Uniform, Bernoulli, Binomial,Poisson), continuous distributions (Uniform, Normal), expectation and variance, sampling distribution theory, joint distributions, covariance and correlation 4. Estimation: properties of estimators, confidence intervals 5. Test of statistical hypotheses: Binomial test, Gaussian test, t-test, power, p-value 6. Regression: simple / multiple regression, tests concerning regression 7. Time series analysis: stochastic processes, stationarity, autocorrelation, filtering **Literature:** Slides				
4	**Competencies** This course gives an introduction to statistical concepts that are useful for research projects in various fields of application and areas of science. Furthermore the students should get a good grasp of the application of these concepts to engineering problems like prediction, optimal testing and estimation.				
5	**Examination Requirements** All students are requested to solve four take home problems. The final exam will be an oral or a written exam, depending on the number of participants (form will be announced second week of course).				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)**				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Robotics, Process Automation, Cognitive Systems				
9	**Responsibility/ Lecturer** *Dr. T. Mildenberger/* Dr. T. Mildenberger				

Mobile Robots					AR-225
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Mobile Robots (MR)	Lecture/ 1 SWS	15 h	45 h	2
	b) Mobile Robots (MR)	Tutorial/ 2 SWS	25 h	65 h	3
2	**Language** English				
3	**Content** 1. Robot Operating System (ROS) 2. Robotics System Toolbox Matlab 3. Sensors, actuators and kinematics of mobile robots 4. Homing and trajectory following 5. Obstacle avoidance 6. Localisation 7. Path planning 8. Online trajectory optimization 9. Mapping and SLAM **Literature:** Siciliano, Khatib: Springer Handbook of Robotics selected papers on mobile robotics from journals and conferences				
4	**Competencies** The students acquire a profound knowledge of fundamental concepts and practical experience on mobile robots. Students are able to solve mobile robotic tasks such as obstacle avoidance, navigation and localization in a self-dependent manner with selected methods and algorithms in ROS/Matlab.				
5	**Examination Requirements** - successful completion of 75% programming assignments (prerequisite for eligibility to the written exam - written exam				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)**				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study:Robotics, Cognitive Systems				
9	**Responsibility/ Lecturer** *apl. Prof. Dr. F. Hoffmann* / apl. Prof. Dr. F. Hoffmann				

Networked Mobile Robot Systems					AR-302
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Netw. Mob. Robot Systems (NRS)	Lecture/ 2 SWS	25 h	65 h	3
b) Netw. Mob. Robot Systems (NRS)	Tutorial/ 1 SWS	15 h	30 h	1,5
c) Netw. Mob. Robot Systems (NRS)	Lab	3 h	2 h	0,5

2 Language

English

3 Content

Concept of Operations: Definitions, Impact and History of Networked Robot Systems, Robot Systems, Use Cases, Business Cases

Information & Communication Technologies: Mobile Radio Networks, Robust Mesh/Relay Communication Protocols, fast handovers, real-time requirements

Swarm strategies: Self learning, controlled mobility, autonomous behavior and learning, distributed systems

Decentralized Mission Scheduling & Task Distribution: Algorithms for strategic goal and tactical task management, autonomous agents, role models, role switching, association of tasks and responsibilities, task vs. communication performance

Performance Evaluation: Event-Driven Simulation, random generators, system models (channel, mobility, protocols), statistical relevance, experiments, analytical modeling (Markov state models)

Literature:

Slides of all lectures will be supplied online

4 Competencies

The course introduces concepts, methods and the performance evaluation of wireless networking, distributed problem solving, cooperative algorithms and swarm based behavior to accomplish easy deployment and appropriate mission scheduling for networked robotics systems.

5 Examination Requirements

The final exam will be an oral (30 minutes) exam.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

We assume that the participants have basic knowledge of mathematical modeling. A basic understanding of fundamental control concepts and distributes systems is helpful but not mandatory.

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems

9 Responsibility/ Lecturer

Jun.-Prof. Dr. Fang-Jing Wu/ Jun.-Prof. Dr. Fang-Jing Wu

Learning in Robotics					AR-310
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Learning in Robotics (LIR)	Lecture/ 2 SWS	25 h	65 h	3
	b) Learning in Robotics (LIR)	Tutorial/ 1 SWS	15 h	45 h	2
2	**Language** English				
3	**Content** 1. Nonlinear System Identification 2. Learning Robot Kinematics and Dynamics 3. Learning Visual-Motor Coordination 4. Dynamic Programming 5. Reinforcement Learning 6. Evolutionary Robotics 7. Learning from Demonstration **Literature:** Slides				
4	**Competencies** The students acquire a profound knowledge of unsupervised and supervised learning in robotic manipulation as well as mobile robotics.				
5	**Examination Requirements** Practical assignments and oral exam.				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)**				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems				
9	**Responsibility/ Lecturer** *apl. Prof. Dr. F. Hoffmann* / apl. Prof. Dr. F. Hoffmann				

Smart Grids					AR-314
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 4 SWS	**Credit Points** 6	**Workload** 180 h

1	**Modul structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self study**	**Credits**
	Smart Grids (SG)	Lecture/ 3 SWS	45 h	90 h	5
	Smart Grids (SG)	Presentation / 1 SWS	10 h	35 h	1
2	**Language** English				
3	**Content** In the past years the energy system has changed drastically. Due to environmental and political reasons, the power generation from renewable energy resources is increasing while conventional power plants are being shut down. This not only means a change of adopted technologies but also a change of the power flow direction in the electrical grid. The uncertainties of the renewable energy resources have to be properly dealt with using appropriate strategies, algorithms and technologies. This has to be done in order to avoid system instabilities causing complete or partial system blackouts. This course will handle the following aspects of the changing electrical energy network: 1. Basics of Energy Engineering 2. Renewable Energy Technologies 3. Distribution Grid Planning 4. Flexibility and Smart Meters 5. Voltage Regulation 6. State Estimation 7. Protection and control functions 8. Electro-mobility				
4	**Competencies** The students successfully finishing the course should be able to • understand the challenges in today's and future electrical energy networks • comprehend the multiple areas of research done in the distribution grids • develop new solution approaches for energy system problems based on their acquired knowledge.				
5	**Examination Requirements** Dependent on the number of participants the final exam is takes place as oral (30 min) or written exam (2h).				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)** Basic knowledge in Electrical Energy Engineering				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Process Automation, Robotics, Cognitive Systems				
9	**Responsibility/ Lecturer** *Dr.-Ing. Ulf Häger* / Dr. –Ing. Ulf Häger				

ROBOT AND INTERFACE MECHANISMS					AR-226
Rota annually SS	**Duration** 1 Semester	**Semester** X. (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Robot and interface mechanisms	Lecture/ 1 SWS	15 h	40 h	2
	b) Robot and interface mechanisms	Tutorial/ 1 SWS	15 h	40 h	2
	c) Robot and interface mechanisms	Practical train-ing / 1 SWS	15 h	40 h	1
2	**Language** English				
3	**Content** 1. Mechanical components a. Energy conductors and transformers b. Control elements and energy storages 2. Robot mechanisms a. Joints and mechanisms b. Direct and inverse kinematics c. Evaluation of mechanisms 3. Human-robot interfaces a. Sensors and stimulators b. Kinematic design c. Interface systems The laboratory part will be a mini design project in which student groups will create their own low-budget haptic human-machine interfaces. **Literature:** • Rinderknecht S: Einführung in die Mechatronik für den Maschinenbau. Shaker, 2018. • Lenarcic J, Bajd T, Stanisic M M: Robot Mechanisms. Springer, 2013. • Hatzfeld C, Kern T A: Engineering Haptic Devices - A Beginner's Guide. Springer, 2014. • Selected research articles.					
4	**Competencies** On successful completion of this module, students will be able to: 1. Distinguish basic mechanical components and select them appropriately in mechanism design. 2. Understand robot mechanisms and apply kinematic calculations for their design and con-trol. 3. Know components of human-robot interfaces and be able to design such systematically.				
5	**Examination Requirements** Presentation (15 minutes) and oral exam (max. 30 minutes)				
6	**Formality of Examination** ☐ Module Finals ☒ Accumulated Grade				
7	**Module Requirements (Prerequisites)**				
8	**Allocation to Curriculum:** Program: Automation & Robotics; Field of study: Robotics, Cognitive Systems				
9	**Responsibility/ Lecturer** JProf. Dr.-Ing. Philipp Beckerle				

HARDWARE SOFTWARE CODESIGN					AR-227
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Hardware Software Codesign	Lecture/ 3 SWS	35 h	50 h	3
	b) Hardware Software Codesign	Tutorial/ 1 SWS	15 h	50 h	2
2	**Language** English				
3	**Content** Design of mixed Hadrware/Software solutions for embedded systems, Understanding of system-level design paradigms, HW/SW partitioning, optimization and evaluation of design quality, Modeling and Performance analysis of safety-critical and real-time embedded systems. **Literature:** [1] „Specification and Design of Embedded Systems“, D. Gajski, Prentice Hall 1994, ISBN 0-13-150731-1 [2] „Digitale Hardware/Software Systeme – Synthese und Optimierung“, J. Teich, Springer Verlag 1997, ISBN 3-540-62433-3				
4	**Competencies** By attending this course, students will learn the design of complex electronic systems at high level of abstractions. This includes the optimized partitioning, scheduling and evaluation of mixed hardware and software design solutions dedicated to embedded systems. The tutorial sessions will present advanced related topics in HW/SW codesign and performance analysis for safety-critical and real-time embedded systems.				
5	**Examination Requirements** Oral exam (max. 40 minutes) or written exam (max. 180 minutes) All students are required to successfully complete 2 out of 4 special assignments in order to be admitted to the final exam.				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)** Basic knowledge of computer architectures, basic knowledge of C programming language.				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: **Cognitive Systems**				
9	**Responsibility/ Lecturer** Prof. Dr.-Ing. Selma Saidi				

DISTRIBUTED AND NETWORKED CONTROL					AR-228
Rota annually SS	**Duration** 1 Semester	**Semester** 2nd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	c) Distributed and Net-worked Control	Lecture/ 2 SWS	25 h	40 h	3
	d) Distributed and Net-worked Control	Tutorial/ 1 SWS	15 h	40 h	2
	e) Distributed and Net-worked Control	Practical trai-ning			

2 Language

English

3 Content

Element 1

Introduction to distributed control and networked systems

- Cyber-physical systems
- Application domains
- Examples

Algebraic graph theory

- Directed graphs and their description
- Matrix representation of graphs
- Analysis tools for graphs

Consensus in multi-agent control

- Control design for consensus
- Convergence analysis
- Leader-follower networks

Synchronisation

- Modelling and interpretation of coupling structures
- Linear and nonlinear settings
- Kuramoto oscillators
- Power-swing equations

Research outlook and case studies

Lehrinhalte Elemente 2 und 3

- Black board exercises, in class computer exercises

Literature:

- Jan Lunze, Networked Control of Multi-Agent Systems, Bookmundo Direct, 2019, ISBN: 9789463867139
- Francesco Bullo, Lectures on Network Systems, 2Kindle Direct Publishing, 2019, ISBN: 978-1986425643

4 Competencies

The students are able to formulate and to solve problems of modelling and control of net-worked control systems and distributed control. The students are able to understand and to analyze the interplay of problem formulation, modelling and system-theoretic solution ap-

	proaches. They know how to apply and to implement distributed and decentralized control schemes for networked linear systems. The students are able to analyze consensus phenomena and synchronization mechanisms arising in coupled systems.
5	**Examination Requirements** Oral exam (max. 30 minutes) or written exam (90 minutes)
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade
7	**Module Requirements (Prerequisites)** • Basics of control engineering (state space description, LQR control, Lyapunov functions) • Basics of ordinary differential equations
8	**Allocation to Curriculum:** Program: Automation & Robotics; Field of study: **Process Automation**, **Robotics**, **Cognitive Systems**
9	**Responsibility/ Lecturer** Prof. Dr.-Ing. Timm Faulwasser

SINGLE -LOOP AND MULTI-LOOP CONTROLLER DESIGN					AR-229
Rota annually WS	**Duration** 1 Semester	**Semester** 3rd (Semester)	**SWS** --SWS	**Credit Points** 3	**Workload** 90 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Single-loop and multi-loop controller design	Lecture/ SWS 2	25 h	25 h	2
	b) Single-loop and multi-loop controller design	Tutorial/ SWS 1	15 h	25 h	1
2	**Language** English				

3 Content

1. Frequency domain single loop controller design
   1.1. Specification of controller performance in the time domain and in the frequency domain
   1.2. Loop shaping: Classical PID and Lead-Lag controller design revisited
   1.3. Design using frequency response approximation (FASTER)
   1.4. Limits of controller performance
   1.5. Internal Model Control
2. Frequency domain multivariable controller design
   2.1. I/O-system description, poles, zeros of MIMO systems
   2.2. Stability criteria
   2.3. Decoupling, sequential loop closure, approximate decoupling, directionality
   2.4. Multivariable frequency response approximation
3. Control structure selection

Literature:

1) Multivariable Feedback Control - Analysis and Design by Sigurd Skogestad and Ian Postlethwaite, 2nd edition, Wiley, 2005

2) Modern Control Engineering by Katsuhiko Ogata, 4th edition, Prentice Hall

4	**Competencies**
5	**Examination Requirements**
6	**Formality of Examination** ☐ Module Finals ☐ Accumulated Grade
7	**Module Requirements (Prerequisites)**
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: **Process Automation**
9	**Responsibility/ Lecturer** Prof. Dr.-Ing. Sebastian Engell

3. Semester

Advanced Process Control					AR-301
Rota annually WS	**Duration** 1 Term	**Semester** 3rd (Semester)	**SWS** 2 SWS	**Credit Points** 3	**Workload** 90 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Advanced Process Control (APC)	Lecture / 1 SWS	15 h	45 h	2
	b) Advanced Process Control (APC)	Tutorial / 1 SWS	15 h	15 h	1
2	**Language** English				
3	**Content** • Analysis of linear dynamic systems: Stability, controllability, observability, poles, zeros. • State space controller design techniques: Eigenvalue and eigenstructure assignment by state feedback, observers, Kalman filter, observers for systems unknown inputs, observer-based control. • Controller design techniques for nonlinear systems: nonlinear observers, extended Kalman filter, gain scheduled controllers, exact feedback linearization. • Advanced model-predictive control: Linear constrained model predictive control, nonlinear model predictive control, direct optimizing control. **Literature:** • Slides • Lecture Notes				
4	**Competencies** The course provides in-depth knowledge of state of the art techniques for advanced process control and prepares for further scientific work in this area and for industrial jobs in process control and operation departments or companies. The students understand the methods listed above and are able to choose the appropriate methods for the solution of practical problems, to synthesize a solution and to evaluate the results.				
5	**Examination Requirements** The final exam will be an oral (20 minutes) or written (1.5 hours) exam, depending on the number of participants (form will be announced second week of course). Active participation and collaboration in 75% of computer exercises is mandatory.				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)** Basic knowledge of dynamic systems and control, as e.g. provided by the course Control Theory and Applications.				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Process Automation Robotics, Cognitive Systems				
9	**Responsibility/ Lecturer** *Prof. Dr. S. Engell/* Prof. Dr. S. Engell				

Mobile Communication Networks					AR-303
Rota annually WS	**Duration** 1 Semester	**Semester** 3rd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Mobile Communication Networks (MCN)	Lecture/ 2 SWS	25 h	65 h	3
	b) Mobile Communication Networks (MCN)	Tutorial/ 1 SWS	15 h	30 h	1,5
	c) Mobile Communication Networks (MCN)	Lab Experiments	3 h	2 h	0,5
2	**Language** English				
3	**Content** Evolution of wide area radio networks: WiMax, Mobile WiMax, LTE and LTE-Advanced. Meshed Networks: Basic concepts, Meshing based on 802.11, .14, .16, Broadband multihop architectures. Interference and Coexistance of Radio Networks: Definition, convolution and application to differential equations. LR-WPANs: ZigBee, Bluetooth, WiMedia and their derivates in control technology Wireless Sensor Networks (WSN) Environment and Content aware Networks: Communication basics for and in between autonomous, moving entities. **Literature:** Slides of all lectures will be supplied online				
4	**Competencies** The course introduces advanced networking concepts with a special focus on wide area coverage and meshing as being used in sensor array networks. The students will achieve capabilities to apply and further develop such systems in the area of mobile robotics.				
5	**Examination Requirements** The final exam will be an oral (30–40 minutes) exam. formal: none; content: none				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)** The participants will leverage knowledge in mobile communication. Basic				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Cognitive Systems Program: Electrical Engineering und Information Technology (ETIT-263)				
9	**Responsibility/ Lecturer** *Prof. Dr. C. Wietfeld/* Prof. Dr. C. Wietfeld				

Computational Intelligence					AR-306
Rota annually WS	**Duration** 1 Semester	**Semester** 3rd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Computational Intelligence (CI)	Lecture/ 2 SWS	25 h	65 h	3
b) Computational Intelligence (CI)	Tutorial/ 1 SWS	15 h	45 h	2

2 Language: English

3 Content

Since the course covers three different aspects of computational intelligence, the contents can best be described following this division into three parts:

1. Artificial Neural Nets: After a short introduction with reference to the biological paradigm, an introduction to threshold logic sets the basics for neural nets. The most important types of nets are covered namely the perceptron, one- and two-layered nets, and Hopfield nets. Supervised and unsupervised learning is discussed, the backpropagation algorithm and enhancements. The content is presented in a way that emphasis the practical and implementation aspects as well as theoretical considerations like limitations and complexity issues.
2. Evolutionary Algorithms: Again stemming from a natural source of inspiration evolutionary algorithms are introduced as an example from the class of general randomized search heuristics. After a description of the main modules (initialization, selection, crossover, and mutation) comes a discussion of typical parameter settings for population sizes and crossover and mutation probability. Then theoretical aspects are considered, the focus is on the analysis of the mean convergence rates.
3. Fuzzy Logic: This final part starts with an introduction to fuzzy sets and fuzzy logic using fuzzy relations and the concept of fuzzy inference. Applications like fuzzy clustering and fuzzy controllers are discussed.

Literature:

- A.E. Eiben and J.E. Smith: Introduction to Evolutionary Algorithms. Corrected 2nd printing. Springer 2007.
- Raul Rojas: Neural Networks - A Systematic Introduction. Springer 1996. Available online.
- G.J. Klir und B. Yuan: Fuzzy Sets and Fuzzy Logic. Prentice Hall 1995.
- F. Höppner, F. Klawonn, R. Kruse und T. Runkler: Fuzzy Cluster Analysis. Wiley 1999.
- Amit Konar: Computational Intelligence: Principles, Techniques and Applications. Springer 2005.

4 Competencies

Computational Intelligence is used as an umbrella term for different approaches that deliver enhanced performance and applicability. It encompasses artificial neural nets, evolutionary algorithms, and fuzzy logic. This course gives a thorough introduction into all three aspects of computational intelligence from the perspective of computer science. It focuses on theoretical aspects as well as typical application scenarios. After attending the course students are expected to have a basic understanding of the working principles, application areas and limitations of the three approaches.

5 Examination Requirements

Mandatory prerequisite for an admission to the module examination is the successful solution of 50 % of the homework presented and discussed in the tutorial. Final module exam is a written exam (90 minutes).

6 Formality of Examination

	☒ Module Finals ☐ Accumulated Grade
7	**Module Requirements (Prerequisites)**
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Robotics, Process Automation, Cognitive Systems
9	**Responsibility/ Lecturer** *Prof. Dr. G. Rudolph/* Prof. Dr. G. Rudolph

Mathematical Simulation Techniques					AR-308
Rota annually WS or SS	**Duration** 1 Semester	**Semester** 2^{nd}/ 3^{rd}	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Mathematical Simulation Techniques (MST)	Lecture/ 2 SWS	25 h	65 h	3
	b) Mathematical Simulation Techniques (MST)	Tutorial/ 1 SWS	15 h	45 h	2
2	**Language:** English				
3	**Content:** Discretization and solution techniques for the numerical simulation of problems in continuum mechanics, as well as their efficient treatment on computer systems are introduced. The course Advanced Engineering Mathematics, a solid background in mathematics, and solid programming skills are assumed. Among the subjects are the following: 1. Practical finite elements: Variational formulation of partial differential equations, weak solutions, Ritz-Galerkin techniques, finite element approximation and analysis, numerical integration, boundary approximation, mesh generation, error control and reliability, solution of linear systems. 2. Computational aspects of fluid dynamics: Conservation laws, compressible and incompressible fluids, spatial discretization (FD, FV, FEM), stabilization techniques, explicit and implicit time stepping schemes, treatment of boundary conditions, projection- and operator-splitting -techniques. 3. High performance computing: Parallel computer architecture, performance-oriented programming, sparse numerical linear algebra, Krylov-subspace and multigrid solvers, preconditioning strategies, domain decomposition methods, shared and distributed memory parallelization with OpenMP and MPI, GPU Computing. 4. Approximation theory: Interpolation and approximation, polynomial spaces, splines and Bézier curves, existence and uniqueness, best-approximation properties, quasi-interpolation, quality assessment and error analysis. **Literature:** References will be given in the courses.				
4	**Competencies** This course provides students with fundamental mathematical simulation techniques that are essential to solve automation problems in robotics as well as in production and engineering processes of all kinds. The entire simulation pipeline is covered in theory and practice. Students are trained to solve real-life complex problems in “Numerics Labs”.				
5	**Examination Requirements** The final exam will be an oral (20 minutes) or written (1.5 hours) exam, depending on the number of participants (form will be announced in the second week of the course).				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)** Course: “Advanced Engineering Mathematics”, solid programming skills				
8	**Allocation to Curriculum:** Program: Autom. & Robot., Field of study: Robotics, Process Automation, Cognitive Systems				
9	**Responsibility/ Lecturer** *Dean of the Mathematics faculty / Lecturers of the Mathematics faculty*				

Batch Process Operation — AR-311

Rota	Duration	Semester	SWS	Credit Points	Workload
annually WS	1 Semester	3rd (Semester)	3 SWS	4	120h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Batch Process Operation (BPO)	Lecture / 2 SWS	25 h	65 h	3
b) Batch Process Operation (BPO)	Tutorial / 1 SWS	15 h	15 h	1

2 Language

English

3 Content

Many chemical and most biochemical production processes are performed as batch processes where finite quantities of material undergo a sequence of production steps in one or several pieces of equipment. Batch processes differ from continuous processes as they are transient (non-stationary) in nature and often different products are produced in the same equipment, leading to scheduling problems. The course extends the knowledge of the students in the field of operation and control of batch processes. It covers the current standards for batch automation as well as the monitoring, control and optimization of individual batch runs.

Literature:

- Handouts
- Slides

4 Competencies

After the course, the students understand the fundamental differences between batch and continuous operation. They know the standards for batch automation and can interact with automation engineers in this domain. They are able to apply state-of-the-art monitoring, control and optimization techniques in industrial batch processes.

5 Examination Requirements

The final exam will be an oral (20 minutes) or written (1.5 hours) exam, depending on the number of participants (form will be announced in the second week of the course). In addition, there will be a graded homework.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

Basic knowledge of mathematical modeling, dynamic systems, and control, as e.g. provided by the course Control Theory and Applications.

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study: Process Automation

9 Responsibility/ Lecturer

Prof. Dr. S. Engell/ Prof. Dr. S. Engell

Process Performance Optimization — AR-312

Rota	Duration	Semester	SWS	Credit Points	Workload
annually WS	1 Semester	3rd (Semester)	4 SWS	5	150 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Process Performance Optimization (PPO)	Lecture / 2 SWS	25 h	65h	3
b) Process Performance Optimization (PPO)	Tutorial / 1 SWS	15 h	15 h	1
c) Process Performance Optimization (PPO)	Lab / 1 SWS	15 h	15 h	1

2 Language

English

3 Content

The course gives an overview of state-of-the-art techniques and of their applications to optimize the performance of chemical and biochemical production processes. The following topics are dealt with:

- Selection of controllers and control structures
- Tuning of standard controllers
- Optimization of the operating conditions by linear programming and nonlinear optimization
- Model predictive control
- Batch trajectory optimization
- Model-based estimation of process variables for monitoring and control
- Process performance monitoring
- Dynamic simulation and operator training systems
- Manufacturing Execution Systems
- Statistical Process Control, Six Sigma
- Operation of regulated life science processes

Literature:

- Handouts
- Slides

4 Competencies

The students acquire an in-depth knowledge of methods and technologies for the improvement of chemical and biochemical production processes by advanced control, model-based methods, data analysis and optimization and continuous improvement. The students acquire a comprehensive overview of the industrial practice in this area.

5 Examination Requirements

The final exam will be an oral (30 minutes) or written (2 hours) exam, depending on the number of participants (form will be announced in the second week of the course). In addition, the successful completion of the lab experiments (including report and final discussion) is required.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

<u>This module is mutually exclusive with the module “Process Optimization”</u>

By receiving credit points for the module “Process Optimization” you cannot receive credit points the module “Process Performance Optimization”.

Basic knowledge of dynamic systems and control is required, as e.g. provided by the course Control Theory and Applications.

8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Process Automation
9	**Responsibility/ Lecturer** *Prof. Dr. S. Engell/* Prof. Dr. S. Engell/ Dr. G. Dünnebier (Bayer Technology Services GmbH)

Real-Time Operating Systems Design and Implementation				AR-315	
Rota annually SS	**Duration** 1 Semester	**Semester** 3rd (Semester)	**SWS** 4 SWS	**Credit Points** 6	**Workload** 180 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Real-Time Operating Systems Design and Implementation	Lecture/ 2 SWS	25 h	65 h	3
b) Real-Time Operating Systems Design and Implementation	Tutorial/ 2 SWS	25 h	65 h	3

2 Language

English

3 Content

Real-time systems play a crucial role in many modern applications and systems, especially when data processing units need to be integrated into physical systems. This module provides basic and advanced knowledge about real-time systems themselves and their application. The events in this module cover the design and analysis to ensure compliance with real-world system conditions. This knowledge is deepened and practiced in the exercises. The module is particularly suitable for students who are interested in research around Cyber Physical Systems and Embedded Systems.**Literature:**
Slides

4 Competencies

The students understand the basic concepts for the design and analysis in real-time systems, in particular worst-case analyzes. Students should be enabled to apply current procedures for verifying the schedulability of real-time systems and scheduling algorithms.

5 Examination Requirements

The final exam will be an oral exam.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

Required knowledge: Solid knowledge of embedded systems, basic knowledge of Operating Systems and C Programming

8 Allocation to Curriculum:

Program: Automation & Robotics, Field of study:Robotics, Cognitive Systems

9 Responsibility/ Lecturer

*Prof. Dr. J. Chen/*Prof. Dr. J. Chen

Online Problems					AR-316
Rota annually WS	**Duration** 1 Semester	**Semester** 3rd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Online Problems	Lecture/ 2 SWS	25 h	65 h	3
	b) Online Problems	Tutorial/ 2 SWS	10 h	50 h	2
2	**Language** English				
3	**Content** 1. Competitive Analysis 2. Randomized Algorithms 3. Deterministic Algorithms 4. Game-Theoretic Foundations 5. Request-Answer Games **Literature:** Allan Borodin, Ran El-Yaniv, ONLINE COMPUTATION AND COMPETITIVE ANALYSIS. Cambridge University Press.				
4	**Competencies** The students identify online problems and their characteristics. They are able to apply suitable methods to find algorithmic solutions. They can evaluate approaches with respect to efficiency, performance and complexity. They know how to design new online algorithms based on the knowledge acquired during the lecture.				
5	**Examination Requirements** The final exam will be an oral or written exam.				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)** Recommended: knowledge in discrete mathematics and foundations of algorithms				
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems				
9	**Responsibility/ Lecturer** *Prof. Dr.-Ing. Uwe Schwiegelshohn/* Prof. Dr.-Ing. Uwe Schwiegelshohn				

Human-Centered Robotics					AR-317
Rota annually WS	**Duration** 1 Semester	**Semester** 3rd (Semester)	**SWS** 3 SWS	**Credit Points** 5	**Workload** 150 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Human-Centered Robotics	Lecture/ 2 SWS	25 h	65 h	3
	b) Human-Centered Robotics	Tutorial/ 1 SWS	10 h	50 h	2
2	**Language:** English				
3	**Content** 1) Introduction and motivation 2) Human-oriented design methods 3) Biomechanics a) Motions, measurement, and analysis b) Biomechanical models 4) Elastic robotics a) Elastic actuators b) Control of elastic robots 5) Human-robot interaction 6) System integration and fault treatment 7) Empirical research methods a) Research process and experiment design b) Research methods, threats, and ethics. **Literature:** - Ott, C. (2008). Cartesian impedance control of redundant and flexible-joint robots. Springer. - Whittle, M. W. (2014). Gait analysis: an introduction. Butterworth-Heinemann. - Burdet, E., Franklin, D. W., & Milner, T. E. (2013). Human robotics: neuromechanics and motor control. MIT press. - Gravetter, F. J., & Forzano, L. A. B. (2018). Research methods for the behavioral sci-ences. Cengage Learning. - Selected research articles.					
4	**Competencies** On successful completion of this module, students will be able to: 1. Tackle the interdisciplinary challenges of human-centered robot design. 2. Use engineering methods for modeling, design, and control to develop human-centered robots. 3. Apply methods from psychology (perception, experience), biomechanics (motion and human models), and engineering (design methodology) and interpret their results. 4. Develop robotic systems that are provide user-oriented interaction characteristics in addition to efficient and reliable operation.					
5	**Examination Requirements:** The final exam will be an oral or written exam.					
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade					
7	**Module Requirements (Prerequisites):** Required knowledge: none					
8	**Allocation to Curriculum:** Program: Automation & Robotics, Field of study:Robotics					
9	**Responsibility/ Lecturer** *P JProf. Dr.-Ing. Philipp Beckerle /* JProf. Dr.-Ing. Philipp Beckerle					

NONLINEAR MODEL PREDICTIVE CONTROL – THEORY and APPLICATIONS					AR-318
Rota annually WS	**Duration** 1 Semester	**Semester** 3rd (Semester)	**SWS** 5 SWS	**Credit Points** 10	**Workload** 300 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Nonlinear Model Predictive Control – Theory and Applications	Lecture/ 3 SWS	35 h	40 h	
	b) Nonlinear Model Predictive Control – Theory and Applications	Tutorial/ 1 SWS	15 h	40 h	
	c) Nonlinear Model Predictive Control – Theory and Applications	Practical training / 1 SWS			
2	**Language** English				

3 Content

Elemente1

Basics of optimal control theory and numerical optimal control

- Optimality condtions for static problems
- Formulation of optimal control problems
- Gateaux derivative
- Pontryagin Maximum Principle
- Indirect and direct solution methodsffiiziente derivative computation

Advanced aspects of optimal control

- Existence of optimal solutions
- Dual variables
- Singular problems
- Dissipativity and turnpike properties

Modell predictive control of sampled-data systems

- Basics of MPC
- Sufficient stability conditions with and without terminal constraints
- Economic cost functions
- Differences of continuous time and discrete time formulations
- Design and implementation aspects

Outlook

- Stochastic and robust MPC
- Limits of MPC

Case studies

- Energy efficiency in technical systems, multi-energy systems, and others

Lehrinhalte Elemente 2 und 3

- Black board and programming sessions (ca 20h at home and ca 10h in course)

Literature:

	• Chachuat, Benoit. *Nonlinear and dynamic optimization: From theory to practice*. Lecture Notes EPFL
4	**Competencies** The students are able to formulate and to solve problems of operation and control of technical systems on their own. The students are able to understand and to analyze the interplay of problem formulation and efficiency aspects of numerical solutions and to deduce problem-specific formulations. They know how to apply and to implement optimization methods to practical problems. Furthermore, the students can tackle complex problems of predictive control by means of abstraction, they are able to document their results in written form. The students are able to design predictive controllers for nonlinear systems and to validate them by means of simulation.
5	**Examination Requirements** Project* oral exam (max. 30 minutes) ** * Elaboration of a project (Simulation and optimization, 50h) and documentation of the results in report form (ca. 20 pages DIN A4) ** The exact examination arrangements will be announced in the second week of the course.
6	**Formality of Examination** ☐ Module Finals ☒ Accumulated Grade
7	**Module Requirements (Prerequisites)** Necessary Requirements: • Basics of control engineering (state space description, LQR control, Lyapunov functions) • Basics of ordinary differential equations Recommended Requirements: • Basic of optimization, Multivariate Control and Optimal Control
8	**Allocation to Curriculum:** Program: Automation & Robotics
9	**Responsibility/ Lecturer** Prof. Dr.-Ing. Timm Faulwasser

General Education II					**AR-372**
Rota SS and WS	**Duration** 1 Semester	**Semester** 2^{nd} / 3^{rd} Semester	**SWS** 4 SWS	**Credit Points** 3	**Workload** 90 h
1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	1. Language Class (German as foreign language)	S/ 4 SWS	45 h	45 h	3
	2. Foreign Language Class (Native speakers in German)	S/ 4 SWS	45 h	45 h	3
	3. Presentation Class	S/ 4 SWS	45 h	45 h	3
2	**Language:** English/ German				

3	**Content** <u>Course 1 or 2</u> Students acquire capabilities to communicate private information in past and present, to name and ask for professions or study subjects and to query simple information on job offers. Furthermore skills to express commands or giving guidance on an entry level, to make appointments or communicate emergencies, e.g. being sick, via phone, are trained. Further skill to be trained are listed but not limited to • understand and phrase phone messages • ask for explanations and express polite support requests or instructions • query or explain a route to a target • read or write invitations and express good wishes • name pieces of clothing and body parts <u>Course 3</u> Students acquire and apply methods for self– and time–organization, to guide negotiations and presentations, organization of workflows, to handle information plethora, self and object presentation.
4	**Competencies** Successful completion of this module will grant knowledge of a non–native language and will have gained or enhanced either cultural knowledge or presentation skills for the chosen target nation. Besides enhancing the general scope of education other key competences are supposed to be enabled. The necessity to freely choose classes for this subject is supposes to strengthen unsupervised learning skills and self–motivation related to academic studies.
5	**Examination Requirements** 3 Credits will be rewarded for either taking a class acknowledged for 1 or 2 or 3. Each class has to be passed by a final examination. Modalities of examinations are subject to the responsible lecturer. Passing the examination and assignment of credits shall be marked on a course–passing certificate.
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade
7	**Module Requirements (Prerequisites)** Each student who chooses a language class for the General Education subject has to opt for a language other than his or her mother language.
8	**Allocation to Curriculum:** Program: Automation & Robotics
9	**Responsibility/ Lecturer** *Dean of the faculty of Electrical Engineering and Information Technology*

Project Group					AR-380
Rota SS and WS	**Duration** 1 Semester	**Semester** 2nd / 3rd Semester	**SWS** -- SWS	**Credit Points** 12	**Workload** 360 h

1	**Modul Structure**				
	Course (Abbreviation)	**Type/ SWS**	**Presence**	**Self Study**	**Credit Points**
	a) Project Group	Project	120h	240 h	12
2	**Language** English/ German				
3	**Content** 1. Organizing an academic task into work packages 2. Assigning the work packages to work teams 3. Processing the work packages within those work teams 4. Coordination of the work teams 5. Combining the findings of the individual work packages to a final result 6. Reviewing the results				
4	**Competencies** By attending the Project Group, students learn to split various tasks into small work packages which then can be handled with little overlapping. The students are able to process different task requirements for example by considering deadlines and economically reasonable use of resources. They have the ability to present the results in front of an expert audience.				
5	**Examination Requirements** The scientific subject of the Project Group's work has to pertain to the research field of Automation and Robotics. The individual achievement of each student has to be reviewed and to be graded.				
6	**Formality of Examination** ☒ Module Finals ☐ Accumulated Grade				
7	**Module Requirements (Prerequisites)**				
8	**Allocation to Curriculum:** Program: Automation & Robotics				
9	**Responsibility/ Lecturer** *Dean of the faculty of Electrical Engineering and Information Technology*				

4. Semester

Master Thesis — AR-400

Rota	Duration	Semester	SWS	Credit Points	Workload
SS and WS	1 Semester	4th Semester	-- SWS	30	900 h

1 Modul Structure

Course (Abbreviation)	Type/ SWS	Presence	Self Study	Credit Points
a) Master Thesis	Master Thesis	-- h	900 h	30

2 Language

English

3 Content

1. Becoming acquainted with an academic task by using specifications
2. Analyzing scientific literature, standards and methods
3. Developing solution approaches
4. Verification and evaluation of the solution approaches
5. Selection and implementation of the most suitable approach
6. Scientific description of the methods and solutions in written form

The scientific subject of the Master Thesis has to correspond to the main subject.

4 Competencies

The students have the ability to process a specified technical and scientific problem of their subject area by using scientific methods. They can evaluate subject literature by relevance and develop and implement new solutions. Furthermore the candidate is capable of presenting relevant aspects and the solution in a written description, which is scientific and well organized.

5 Examination Requirements

A final talk of the student is the module exam. Apart from that the student has to participate actively in at least 5 talks of other students.

6 Formality of Examination

☒ Module Finals ☐ Accumulated Grade

7 Module Requirements (Prerequisites)

The Master Theses cannot be started before receiving 81 credit points within the curriculum of the Master Program.

The subject of the Master Thesis has to be assigned to the student`s major field of study.

8 Allocation to Curriculum:

Program: Automation & Robotics

9 Responsibility/ Lecturer

Dean of the faculty of Electrical Engineering and Information Technology