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.2023

## 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 vom 15.04.2020 gegenüber der Version vom 20.09.2019:

- 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“

# Änderungen vom 14.07.2021 gegenüber der Version vom 15.04.2020:

- Wegfall der Module AR-207 „Process Optimization“, AR-226 „Robot and interface mechanisms“ und AR-317 „Human-Centered Robotics”
- Neuaufnahme des Moduls AR-230 „Practical Distributed Optimization in julia“
- Neuaufnahme des Moduls AR-231 „Remote Sensing“
- Neuaufnahme des Moduls AR-232 „Machine Learning Methods for Engineers“
- Neuaufnahme des Moduls AR-319 “Mobile and Pervasive Computing”
- Frau Prof. Dr. Selma Saidi übernimmt das Modul AR-103 „Computer Systems“
- Aktualisierung der Modulverantwortlichkeit in den Modulen AR-102, AR-205, AR-206, AR-220, AR-221, AR-222, AR-229, AR-301, AR-311, AR-312
- Überarbeitung Modul AR-201 „Application of Robots“: Erhöhung LP von 3 auf 5
- Überarbeitung Modul AR-301 „Advanced Process Control“: Erhöhung LP von 3 auf 6
- Überarbeitung Modul AR-205 „Process Automation“: Verringerung der LP von 8 auf 4
- Überarbeitung Modul AR-220 „Logic Control“: Verringerung der LP von 6 auf 3, Ergänzung des Schwerpunkts „Process Automation"

# Änderungen vom 19.10.2022 gegenüber der Version vom 14.07.2021:

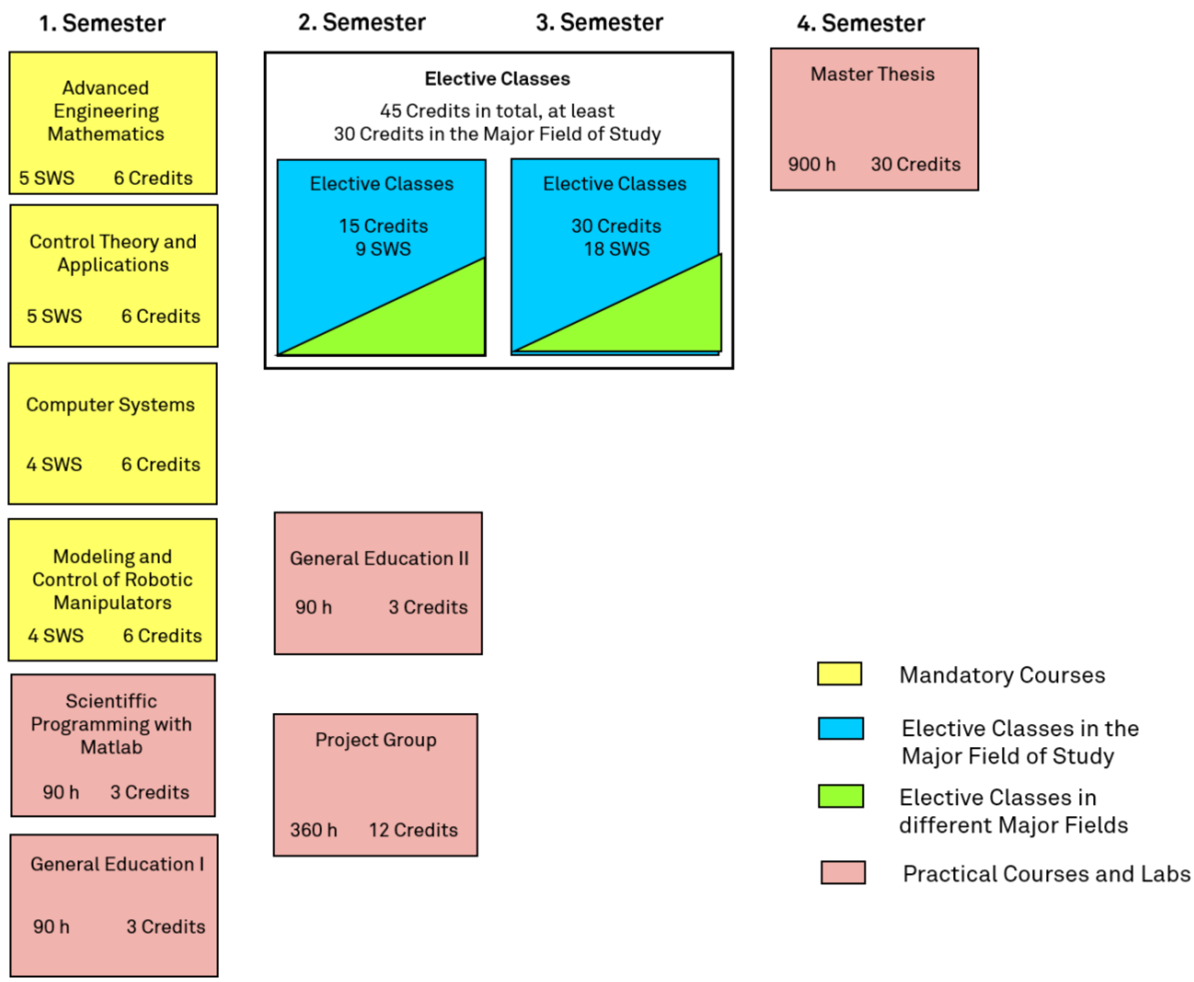
- Neuaufnahme des Moduls: AR-233 „Optimal Power Flow Problems“
- Neuaufnahme des Moduls: AR-234 „Mobile Radio Networks 1“
- Neuaufnahme des Moduls: AR-235 „Mobile Radio Networks 2“
- Neuaufnahme des Moduls: AR-236 „Embedded Autonomy“
- Neuaufnahme des Moduls: AR-320 „Machine Learning and optimal Control”
- Aktualisierung des Moduls AR-227: „Hardware Software Codesign“, Erhöhung von. 5 auf 10 CP
- Aktualisierung des Moduls AR-301: „Advanced Process Ciontrol“, Senkung von 6 auf 5 CP
- Aktualisierung des Moduls AR-310: neuer Titel „**Machine** Learning in Robotics“
- Wegfall des Moduls AR-303: „Mobile Communication Networks”

## Änderungen vom XX.04.2023 gegenüber der Version vom 19.10.2022:

- Aktualisierung des Moduls AR-210
- Neuaufnahme der Module AR-237 und AR-321
- Wegfall der Module AR-220 und AR-221

# Inhaltsverzeichnis

## 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**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>$1^{st}$ (Semester) | **SWS**<br>5 SWS | **Credit Points**<br>6 | **Workload**<br>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. Linear Algebra: Vector spaces, matrices and equation systems, linear maps, Jordan-, LU-, QR-, and singular value decomposition, numerical aspects.
2. Differential Equation: Linear systems, differential equations with constant coefficients.
3. Laplace-Transform and Fourier Series
4. Differential Calculus with several variables: Derivatives, inverse and implicit functions, Taylor expansion and extreme values.
5. Stability of Differential Equations: Theorems of Ljapunov and Poincaré-Ljapunov.
6. Variational Calculus

**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 department/* Lecturers of the Mathematics department

| Control Theory and Applications | | | | | AR-102 |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>1st (Semester) | **SWS**<br>5 SWS | **Credit Points**<br>6 | **Workload**<br>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**

1. 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.
2. Linear state space theory: Autonomous behavior, eigenvalues, eigenvectors, Jordan form, controllability and pole assignment, LQ-optimal control, observability, observers, observer-based control, Kalman decomposition.
3. 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.
4. Design of single-loop controllers: Internal stability, performance specification, classical SISO controller design, robust stability and performance, performance limitations
5. 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 mid-term 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.-Ing. S. Engell and Prof. Dr. S. Lucia* / Prof. Dr.-Ing. S. Engell and Prof. Dr. S. Lucia

| Computer Systems | | | | | AR-103 |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>$1^{st}$ (Semester) | **SWS**<br>4 SWS | **Credit Points**<br>6 | **Workload**<br>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. torage 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**

*Prof. Dr. Selma Saidi/* Prof. Dr. Selma Saidi

| Modeling and Control of Robotic Manipulators | | | | | AR-106 |
|---|---|---|---|---|---|
| **Rota** annually WS | **Duration** 1 Semester | **Semester** $1^{st}$ (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**<br>English | | | | |
| 3 | **Content**<br>1. Spatial Representations<br>2. Direct Kinematics<br>3. Differential Kinematics<br>4. Dynamics<br>5. Actuators and Sensors<br>6. Motion Control<br>7. Interaction Control<br>8. Robotics System Toolbox and ROS<br><br>**Literature:**<br>• Sciavicco, Siciliano: Modelling and Control of Robotic Manipulators | | | | |
| 4 | **Competencies**<br>This course provides the students with a profound background of modelling, planning and control of robotic manipulators.<br>The students acquire practical experience in robot kinematics, dynamics and motion control under ROS/Matlab. | | | | |
| 5 | **Examination Requirements**<br>written exam (2 hours) | | | | |
| 6 | **Formality of Examination**<br>☐ Module Finals ☒ Accumulated Grade | | | | |
| 7 | **Module Requirements (Prerequisites)** | | | | |
| 8 | **Allocation to Curriculum:**<br>Mandatory Course<br>Program: Automation & Robotics) | | | | |
| 9 | **Responsibility/ Lecturer**<br>*apl. Prof. Dr. F. Hoffmann/* apl. Prof. Dr. F. Hoffmann | | | | |

| Scientific Programming with Matlab in Engineering | | | | | | AR-105 |
|---|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>$1^{st}$ (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>3 | | **Workload**<br>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

<table>
<tr><th colspan="2">General Education I</th><th colspan="4"></th><th>AR-371</th></tr>
<tr><td colspan="2">Rota<br>annually WS</td><td>Duration<br>1 Semester</td><td>Semester<br>1st Semester</td><td>SWS<br>4 SWS</td><td>Credit Points<br>3</td><td>Workload<br>90 h</td></tr>
<tr><td rowspan="5">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) Language Class (German as foreign language)</td><td>Seminar/ 4 SWS</td><td>45 h</td><td>45 h</td><td>3</td></tr>
<tr><td colspan="2">b) Foreign Language Class (Native speakers in German)</td><td>Seminar/ 4 SWS</td><td>45 h</td><td>45 h</td><td>3</td></tr>
<tr><td colspan="2">c) Presentation Class</td><td>Seminar/ 4 SWS</td><td>45 h</td><td>45 h</td><td>3</td></tr>
<tr><td>2</td><td colspan="6">Language: English/ German</td></tr>
<tr><td>3</td><td colspan="6">Content<br><u>Course 1 or 2</u><br>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<br>• understand and phrase phone messages<br>• ask for explanations and express polite support requests or instructions<br>• query or explain a route to a target<br>• read or write invitations and express good wishes<br>• name pieces of clothing and body parts<br><u>Course 3</u><br>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.</td></tr>
<tr><td>4</td><td colspan="6">Competencies<br>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.</td></tr>
<tr><td>5</td><td colspan="6">Examination Requirements<br>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.</td></tr>
<tr><td>6</td><td colspan="6">Formality of Examination<br>☒ Module Finals ☐ Accumulated Grade</td></tr>
<tr><td>7</td><td colspan="6">Module Requirements (Prerequisites)<br>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.</td></tr>
<tr><td>8</td><td colspan="6">Allocation to Curriculum:<br>Program: Automation & Robotics</td></tr>
<tr><td>9</td><td colspan="6">Responsibility/ Lecturer<br>Dean of the faculty of Electrical Engineering and Information Technology</td></tr>
</table>

# 2. Semester

| Application of Robots | | | | | AR-201 |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>150 h |

| | | | | | |
|---|---|---|---|---|---|
| 1 | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Application of Robots (AoR) | Lecture/ 2 SWS | 25 h | 65 h | 3 |
| | b) Application of Robots (AoR) | Tutorial / 1 SWS | 15 h | 45 h | 2 |

**2 Language**

English

**3 Content**

This lecture covers applications of industrial robots and their specific requirements on the components of a robot system, on the properties of the robot mechanics and it's controller as well as on the programming methods. A special focus is on the simulation-based offline programming and it's automation for various robot applications. It also covers PLCs as an element of many automation systems and some basics of machine learning in robot control. Topics:

- Production processes with robots:
  e. g. primary shaping, metal forming, cutting, joining, surface coating
- Robot controllers
- Programmable logic controllers (PLC)
- Robot effectors
- Sensors and vision systems
- Simulation Systems and Offline-Programming
- Basics of Machine Learning in Robot Programming

**4 Competencies**

After the successful participation in this course participants are able to assess the requirements on a robotic system deriving from the characteristics of different applications. They can choose appropriate kinematic concepts and components of robot systems depending on a given task. This includes the choice of appropriate sensor types and the design of vision systems. They will be able to evaluate different methods of robot programming with regard to their suitability for specific application areas. They will have a basic understanding of the benefits of machine learning in robot control.

**5 Examination Requirements**

The final exam will be an oral (30 minutes) or written (1 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**

*PD Dr. J. Bickendorf/* PD Dr. J. Bickendorf

| Scheduling Problems and Solutions | | | | | AR-202 |
|---|---|---|---|---|---|
| **Rota**<br>bi-annually SS | **Duration**<br>1 Semester | **Semester**<br>$2^{nd}$ (Semester) | **SWS**<br>7 SWS | **Credit Points**<br>10 | **Workload**<br>300 h |

| | | | | | |
|---|---|---|---|---|---|
| 1 | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Scheduling Problems and Solutions (SPaS) | Lecture/ 4 SWS | 45h | 115 h | 6 |
| | b) Scheduling Problems and Solutions (SPaS) | Tutorial/ 2 SWS | 25 h | 75 h | 3 |
| | c) Scheduling Problems and Solutions (SPaS) | Lab/ 1 SWS | 10 h | 20 h | 1 |

**2 Language**

English

**3 Content Elements 1 and 2**

1. Scheduling language and classes of schedules
2. Complexity
3. Single machine environments: makespan and total weighted completion time, lateness and tardy jobs, total tardiness and a non-regular objective function, a simple bicriterial problem
4. Online problems in single machine environments
5. Parallel machine environments: makespan, total weighted completion time, lateness, and online problems
6. Flow shop, job shop, and open shop problems

**Content Element 3:** Practical approaches to solve scheduling problems including the use of Matlab and CPLEX

**Literature**

- Michael Pinedo: Scheduling - Theory, Algorithms and Systems, 4th edition, Springer Verlag, ISBN: 978-1-461-41986-0, 2012

**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**

Oral exam (40 min)

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)**

Good knowledge in fundamentals of discrete mathematics and basics 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

| Process Automation | | | | | AR-205 |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>4 SWS | **Credit Points**<br>5 | **Workload**<br>150 h |

**1 Modul Structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self Study | Credit Points |
|---|---|---|---|---|
| a) Logic Control (LC) | Lecture / 1 SWS | 12,5 h | 32,5 h | 1,5 |
| b) Logic Control (LC) | Tutorial / 1 SWS | 12,5 h | 32,5 h | 1,5 |
| c) Process Control Lab | Lab / 2 SWS | 22,5 h | 37,5 h | 2 |

**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 introduces 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.

1. Introduction: motivation and application examples for logic control
2. Mathematical foundations: Boolean algebra and functions
3. Hardware realization of logic controllers and fundamentals of PLC programming
4. Programming languages according to the international standard IEC 61131-3 (including function block diagrams and the specification of sequential controls by sequential function charts)

(c) A Process Control Lab consisting of five practical lab experiments (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 the tasks of a logic controller and can formally specify its behavior. They are able to implement simple logic controllers. 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). The requirements for the laboratory are described in appendix A.

**6 Formality of Examination**

☒ Module Finals ☐ Accumulated Grade

| | |
|---|---|
| **7** | **Module Requirements (Prerequisites)**<br>The lab course builds upon the course Control Theory and Applications which is compulsory in the first semester. |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Process Automation<br>As major field of study in Process Automation, this course is mandatory. |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. S. Engell and Prof. Dr. S. Lucia /* Prof. Dr.-Ing. S. Engell and Prof. Dr. S. Lucia |

| Data-Based Dynamic Modeling | | | | | AR-206 |
|---|---|---|---|---|---|
| **Rota**<br>After announcement | **Duration**<br>1 Semester | **Semester**<br>$2^{nd}$ (Semester) | **SWS**<br>2 SWS | **Credit Points**<br>3 | **Workload**<br>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**<br>English | | | | |
| **3** | **Content**<br>1. Identification of simple models from step responses.<br>2. Parameter identification: Basic idea, mathematical description of sampled systems, ARX, ARMAX and OE estimation.<br>3. Modeling using nonlinear black box models (perceptron neural nets, radial-basis-function nets), training, dynamic models, quality of neural net models.<br>4. Model errors: Sources of errors, limits of model accuracy, model accuracy and controller performance.<br>The course takes place in the second half of the semester.<br><br>**Literature:**<br>• Slides<br>• Handouts | | | | |
| **4** | **Competencies**<br>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**<br>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**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Basic knowledge of dynamic systems as e.g. provided by the course Control Theory and Applications. | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Process Automation Robotics, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. S. Engell and Prof. Dr. S. Lucia* / Prof. Dr.-Ing. S. Engell and Prof. Dr. S. Lucia | | | | |

| **Computer Vision** | | | | | **AR-210** |
|---|---|---|---|---|---|
| **Rota**<br>Summer or Winter Term by Announcement | **Duration**<br>1 Semester | **Semester**<br>2nd / 3rd (Semester) | **SWS**<br>4 SWS | **Credit Points**<br>6 | **Workload**<br>180 h |

| | | | | | |
|---|---|---|---|---|---|
| **1** | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Computer Vision (CV) | Lecture/ 2 SWS | 25 h | 65 h | 2 |
| | b) Computer Vision (CV) | Tutorial/ 2 SWS | 25 h | 65 h | 2 |

**2** **Language:**

English

**3** **Content**

For the majority of living beings 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 including the perception and representation of colors. Afterwards, methods for the computation of local feature representations (e.g. descriptors, depth, or motion) and for the extraction of image primitives (e.g. regions, contours and keypoints) are presented. Finally, the lecture focusses on appearance based object recognition techniques that lie at boundary between image segmentation and scene interpretation. Especially, deep neural networks will be covered that currently are the dominant methodology for the solution of machine perception tasks.

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:**

- Gonzalez, Rafael C.; Woods, Richard E.: Digital Image Processing, Prenctice Hall, 2nd Ed., 2002.
- Forsyth, David A.; Ponce, Jean: Computer Vision - A Modern Approach, Prentice Hall, 2003.
- Szeliski, Richard: Computer Vision, Springer, 2010

**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 for themselves in innvative application scenarios - as, e.g., robotics and man-machine interaction – and to assess their strengths and limitations.

**5** **Examination Requirements**

*Module examination:* oral examination (30–45 minutes)

*Course achievements:* as per announcement

**6** **Formality of Examination**

☒ Module Finals ☐ Accumulated Grade

**7** **Module Requirements (Prerequisites)**

*Prerequisite Knowledge:* Basic knowledge of mathematics

*Desirable knowledge:* Programming skills

**8** **Allocation to Curriculum:**

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

**9** **Responsibility/ Lecturer**

| | |
|---|---|
| | *Prof. Dr.-Ing. G. Fink/* Prof. Dr.-Ing. G. Fink |

| **3 D Computer Vision** | | | | | **AR-213** |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>$2^{nd}$ (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>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 | Duration | Semester | SWS | Credit Points | Workload |
|---|---|---|---|---|---|
| annually WS or SS | 1 Semester | 2nd/3rd (Semester) | 3 SWS | 5 | 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 department* / Lecturers of the Mathematics department

| Cyber-Physical System Fundamentals | | | | | AR-215 |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>3rd (Semester) | **SWS**<br>4 SWS | **Credit Points**<br>6 | **Workload**<br>180 h |

**1 Modul Structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self Study | Credit Points |
|---|---|---|---|---|
| a) Cyber-Physical System Fundamentals (CPSF) | Lecture/ 4 SWS | 45 h | 75 h | 4 |
| b) Cyber-Physical System Fundamentals (CPSF) | Lab | 60 h | | 2 |

**2 Language:**

English

**3 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 – Embedded Systems Foundations of Cyber-Physical Systems, and the Internet of Things, Springer, 2021
- Technical documentation fort he used finite state machine design tool (StateMate or similar)

**4 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.

**5 Examination Requirements**

The students have to pass both the lab and the finals.

**6 Formality of Examination**

☒ Module Finals ☐ Accumulated Grade

**7 Module Requirements (Prerequisites)**

Basic knowledge in programming as well as finite-state machines.

**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

| Logistics of Chemical Production Processes | | | | | AR-222 |
|---|---|---|---|---|---|
| **Rota**<br>After Announcement | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>2 SWS | **Credit Points**<br>3 | **Workload**<br>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**<br>English | | | | |
| **3** | **Content**<br>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.<br><br>**Literature:**<br>• Handouts<br>• Slides | | | | |
| **4** | **Competencies**<br>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**<br>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**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)** | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Process Automation | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. S. Engell and Prof. Dr. S. Lucia* / Dr. Christian Sonntag | | | | |

| Statistics for Researchers in Engineering Sciences | | | | | AR-223 |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>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**<br>English | | | | |
| **3** | **Content**<br>1. Empirical distributions and explanatory data analysis: frequency tables, bar charts, histograms, distribution characteristics<br>2. Probability theory: conditional probability, independence<br>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<br>4. Estimation: properties of estimators, confidence intervals<br>5. Test of statistical hypotheses: Binomial test, Gaussian test, t-test, power, p-value<br>6. Regression: simple / multiple regression, tests concerning regression<br>7. Time series analysis: stochastic processes, stationarity, autocorrelation, filtering<br><br>**Literature:**<br>• Slides | | | | |
| **4** | **Competencies**<br>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**<br>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**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)** | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Robotics, Process Automation, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Dr. T. Mildenberger/* Dr. T. Mildenberger | | | | |

| **Mobile Robots** | | | | | **AR-225** |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>4 SWS | **Credit Points**<br>5 | **Workload**<br>150 h |

**1 Modul Structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self Study | Credit Points |
|---|---|---|---|---|
| a) Mobile Robots (MR) | Lecture/ 2 SWS | 30 h | 30 h | 3 |
| b) Mobile Robots (MR) | Tutorial/ 2 SWS | 30 h | 60 h | 2 |

**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 (Vector Field Histograms)
6. Localisation
7. Path planning (Rapidly Exploring Random Trees, Probabilistic Roadmap)
8. Navigation (Pure Pursuit, ROS Navigation Stack)
9. Online trajectory optimization
10. 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**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>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**

1. Concept of operations: definitions, impact and history of networked robot systems, use cases.
2. Localization: basic localization technologies, indoor and outdoor localization systems, proximity sensing and localization, mobility analytics.
3. Information & communication technologies: local area networks, mobile radio networks, robust mesh/relay communication protocols, routing protocols, wireless mesh networks and standards, fast handovers.
4. Swarm strategies: self-learning, controlled mobility, autonomous behavior and learning, distributed coordination.
5. Decentralized mission scheduling & task distribution: Algorithms for strategic goal and tactical task management, autonomous agents, role models, role switching, association of tasks and responsibilities, tasks vs. communication performance
6. Performance evaluation: event-driven simulations, system and analytical modeling (for channel conditions, mobility, communication protocols).

**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

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

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|---|---|---|---|---|---|
| **1** | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Machine Learning in Robotics (LIR) | Lecture/ 2 SWS | 25 h | 65 h | 3 |
| | b) Machine Learning in Robotics (LIR) | Tutorial/ 1 SWS | 15 h | 45 h | 2 |
| **2** | **Language**<br>English | | | | |
| **3** | **Content**<br>1. Fundamentals of Machine Learning<br>2. Nonlinear Regression<br>3. Neural Networks<br>4. Deep Learning<br>5. Reinforcement Learning<br><br>**Literature:**<br>Ian Goodfellow, Yoshua Bengio, Aaron Courville, Deep Learning, MIT Press, 2016<br>Bruno Siciliano, Oussama Khatib: Springer Handbook of Robotics, 2nd edition, 2008<br>Richard Sutton, Andrew G. Barton, Reinforcement Learning an Introduction, 2nd edition, MIT Press, 2018<br>Selected publications from journals and conferences. | | | | |
| **4** | **Competencies**<br>The students acquire a profound knowledge of theoretical concepts and practical applications of machine learning in robotics. Students are able to solve machine learning tasks for supervised and reinforcment learning with methods and algorithms within Matlab and ROS. | | | | |
| **5** | **Examination Requirements**<br>Written exam | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>none | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*apl. Prof. Dr. F. Hoffmann/* apl. Prof. Dr. F. Hoffmann | | | | |

| Smart Grids | | | | | AR-314 |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>$2^{nd}$ (Semester) | **SWS**<br>4 SWS | **Credit Points**<br>6 | **Workload**<br>180 h |

**1 Modul structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self study | Credits |
|---|---|---|---|---|
| a) Smart Grids (SG) | Lecture/ 3 SWS | 45 h | 90 h | 5 |
| b) 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. Renewable Energy Technologies
2. Microgrids
3. Distribution Grid Planning
4. Flexibility and Smart Meters
5. Voltage Regulation
6. State Estimation
7. Protection and control functions
8. Grid Automation
9. Electro-mobility

**Literature**

CIGRE WG C6.22: "Microgrids 1 Engineering, Economics, & Experience", Technical Report 635, 2015;
https://www.dena.de/fileadmin/dena/Dokumente/Themen_und_Projekte/Energiesysteme/dena-Studie_Systemdienstleistungen_2030/dena_Ancillary_Services_Study_2030.pdf

Smart Grids: Hadjsaid, Nouredine a. Jean-Claude Sabonnadiere, Wiley-ISTE, 2012, ISBN: 9781848212619

**4 Competencies**

The students successfully finishing the course should be able to

- understand the challenges in today's and future electrical energy distribution grids
- 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 (90 min).

**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

| **Hardware Software Codesign** | | | | | **AR-227** |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>10 | **Workload**<br>300 h |

| | | | | | |
|---|---|---|---|---|---|
| **1** | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Hardware Software Codesign | Lecture/ 3 SWS | 35 h | 135 h | 6 |
| | b) Hardware Software Codesign | Tutorial/ 1 SWS | 15 h | 50 h | 2 |
| | **c)** Hardware Software Codesign | Practical Course | 25 h | 40 | 2 |
| **2** | **Language**<br>English | | | | |
| **3** | **Content**<br>1. Design of mixed Hadrware/Software solutions for embedded systems,<br>2. Understanding of design components<br>3. Understanding of system-level design paradigms,<br>4. HW/SW partitioning<br>5. Optimization methods<br>6. Performance analysis measures<br>7. Evaluation methods<br>8. Modeling and Performance analysis of safety-critical and real-time embedded systems.<br>**Literature**<br>[1] „Specification and Design of Embedded Systems", D. Gajski, Prentice Hall 1994, ISBN 0-13-150731-1<br>[2] „Digitale Hardware/Software Systeme – Synthese und Optimierung", J. Teich, Springer Verlag 1997, ISBN 3-540-62433-3 | | | | | |
| **4** | **Competencies**<br>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. During the Tutorials the students acquire knowledge about advanced related topics in HW/SW codesign and performance analysis for safety-critical and real-time embedded systems.<br>During the practical exercises to the lecture the students will apply the theoretical knowledge of the lecture considering real-world scenarios to allow a better accessibility to the methods explained. Starting from simple system specification the students will use tools for partitioning, optimization and performance analysis to synthesize the hardware/software system. | | | | | |
| **5** | **Examination Requirements**<br>• Oral exam (max. 40 minutes) or written exam (max. 180 minutes)<br>All students are required to successfully complete 2 out of 4 special assignments in order to be admitted to the final exam.<br>• All students are required to successfully complete the lab tasks. | | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Basic knowledge of computer architectures, basic knowledge of C programming language. | | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Cognitive Systems | | | | | |

| | |
|---|---|
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. Selma Saidi/* Prof. Dr.-Ing. Selma Saidi |

| Distributed and Networked Control | | | | | AR-228 |
|---|---|---|---|---|---|
| **Rota** | **Duration** | **Semester** | **SWS** | **Credit Points** | **Workload** |
| annually SS | 1 Semester | 2nd (Semester) | 3 SWS | 5 | 150 h |

| | | | | | |
|---|---|---|---|---|---|
| 1 | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Distributed and Networked Control | Lecture/ 2 SWS | 25 h | 40 h | 3 |
| | b) Distributed and Networked Control | Tutorial/ 1 SWS | 15 h | 40 h | 2 |
| | c) Distributed and Networked Control | Practical training | | | |

**2 Language**

English

**3 Content**

Element 1

1. Introduction to distributed control and networked systems
    a. Cyber-physical systems
    b. Application domains
    c. Examples
2. Algebraic graph theory
    a. Directed graphs and their description
    b. Matrix representation of graphs
    c. Analysis tools for graphs
3. Consensus in multi-agent control
    a. Control design for consensus
    b. Convergence analysis
    c. Leader-follower networks
4. Synchronisation
    a. Modelling and interpretation of coupling structures
    b. Linear and nonlinear settings
    c. Kuramoto oscillators
    d. Power-swing equations
5. Research outlook and case studies

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 networked control systems and distributed control. The students are able to understand and to analyze the interplay of problem formulation, modelling and system-theoretic solution approaches. 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)**<br>Basics of control engineering (state space description, LQR control, Lyapunov functions)<br>Basics of ordinary differential equations | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics; Field of study: Process Automation, Robotics, Cognitive Systems | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. Timm Faulwasser/* Prof. Dr.-Ing. Timm Faulwasser | |

## Single-loop and multi-loop controller design — AR-229

| Rota | Duration | Semester | SWS | Credit Points | Workload |
|---|---|---|---|---|---|
| After Announcement | 1 Semester | 2nd (Semester) | 3 SWS | 3 | 90 h |

**1 Modul Structure**

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

**2 Language**

English

**3 Content**

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

**Literature:**

- Multivariable Feedback Control - Analysis and Design by Sigurd Skogestad and Ian Postlethwaite, 2nd edition, Wiley, 2005
- 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 and Prof. Dr. S. Lucia* / Prof. Dr.-Ing. Sebastian Engell and Prof. Dr. S. Lucia

| Practical Distributed Optimization in julia | | | | | | AR-230 |
|---|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | | **Workload**<br>150 h |
| **1** | **Modul Structure** | | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | | **Credit Points** |
| | a) Practical Distributed Optimization in julia | Lecture/ 1 SWS | 15 h | 600 h | | 2 |
| | b) Practical Distributed Optimization in julia | Tutorial/ 2 SWS | 25 h | 50 h | | 3 |
| **2** | **Language**<br>English | | | | | |
| **3** | **Content**<br>Element 1<br>1. Begrifflichkeiten zu verteilten Algorithmen und Multi-Agenten Systemen im Kontext von Informatik, Regelung und Optimierung<br>2. verteilte und dezentrale Ansätze zur Lösung konvexer und nicht-konvexer Optimierungsprobleme<br>3. Implementierung der Optimierungsansätze in der Programmiersprache julia (flipped classroom)<br>4. Behandelte Algorithmen sind u.a.<br>a. Dekomposition von Sequential Quadratic Programming und Interior Point Methoden<br>b. Augmented Lagrangian<br>c. Dual Decomposition<br>d. Augmented Direction of Multipliers Methods (ADMM)<br>e. Augmented Lagrangian Inexact Newton (ALADIN)<br>5. Anwendungsbeispiele aus Regelung und Automation<br>6. Element 2<br>7. Einführung in JULIA<br>8. Umsetzung von Algorithmen der Optimierung in JULIA<br>9. Fallstudien für technische Anwendungen<br>**Literature**<br>• Boyd, Stephen, Neal Parikh, Eric Chu, Borja Peleato, und Jonathan Eckstein. „Distributed Optimization and Statistical Learning via the Alternating Direction Method of Multipliers“. Foundations and Trends® in Machine Learning 3, Nr. 1 (2011): 1–122.<br>• Bertsekas, Dimitri P., und John N. Tsitsiklis. Parallel and Distributed Computation: Numerical Methods. Athena Scientific, 1997. | | | | | |
| **4** | **Competencies**<br>Studierende sind der Lage Fragestellungen der Multi-Agenten Optimierung in technischen Anwendungen mit Hilfe mathematischer Methoden selbstständig zu bewältigen. Insbesondere sind sie in der Lage anwendungsbezogene Probleme zu analysieren und in abstrakte Optimierungsprobleme zu transkribieren und diese mit Hilfe geeigneter Multi-Agenten Ansätze, d.h. verteilten und dezentralen Optimierungsverfahren, zu lösen.<br>Studierende beherrschen die Grundlagen der der Programmiersprache julia und sind in der Optimierungsprobleme darin zu lösen. Sie haben einen Überblick über etablierte Methoden zu Lösung konvexer und nicht-konvexer Optimierungsprobleme mit Hilfe von Multi-Agentenansätzen für verteilte und dezentrale Optimierungsverfahren. | | | | | |
| **5** | **Examination Requirements**<br>Oral exam (max. 30 minutes) or written project work. More information latest on the 2nd lecture. | | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals | | | ☐ Accumulated Grade | | |
| **7** | **Module Requirements (Prerequisites)**<br>Vorkenntnisse zur numerischen Optimierung | | | | | |

| | | |
|---|---|---|
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics; Field of study: Process Automation, Robotics, Cognitive Systems | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. Timm Faulwasser/* Prof. Dr.-Ing. Timm Faulwasser | |

| Remote Sensing | | | | | AR-231 |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>150 h |

| | | | | | |
|---|---|---|---|---|---|
| **1** | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Remote Sensing | Lecture/ 2 SWS | 30 h | 60 h | 3 |
| | b) Remote Sensing | Tutorial/ 1 SWS | 15 h | 45 h | 2 |
| **2** | **Language**<br>English | | | | |
| **3** | **Content**<br>1. Sensorsysteme zur Aufnahme von Luft- und Satellitenbildern<br>2. Eigenschaften von Luft- und Satellitenbildern in unterschiedlichen Spektralbereichen<br>3. Korrekturverfahren für atmosphärische und topographische Effekte<br>4. Verfahren zur Analyse von Bilddaten in Remote-Sensing-Anwendungen<br>5. Verfahren zur Analyse von Spektraldaten in Remote-Sensing-Anwendungen<br>6. Orthorektifizierung, Georeferenzierung und Koregistrierung von Luft- und Satellitenbildern<br>7. Klassifikationsverfahren für Multi- und Hyperspektralbilddaten<br>8. Praktische Anwendungsbeispiele aus der aktuellen Forschung<br><br>**Literature**<br>Schowengerdt, R.A.: Remote Sensing: Models and Methods for Image Processing. 3rd Edition, Academic Press, 2007. | | | | |
| **4** | **Competencies**<br>Nach erfolgreichem Abschluss des Moduls beherrschen die Studierenden die wesentlichen Grundlagen des Remote Sensing sowie die hierfür benötigten Signal- und Bildverarbeitungsverfahren. Die Studierenden können Aufgabenstellungen für Systeme zum Remote Sensing aus unterschiedlichen Anwendungsbereichen einordnen und selbständig mit eigenständig ausgewählter Methodik lösen. | | | | |
| **5** | **Examination Requirements**<br>The final exam takes place as oral (40 min) or written exam (2h). | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Knowledge in basics of electrical engineering, signal processing, image processing | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics; Field of study: Robotics, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr. rer.nat. Christian Wöhler/* Prof. Dr. rer.nat. Christian Wöhler | | | | |

| Machine Learning Methods for Engineers | | | | | AR-232 |
|---|---|---|---|---|---|
| **Rota**<br>annually SS | **Duration**<br>1 Semester | **Semester**<br>2nd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>150 h |

| | | | | | |
|---|---|---|---|---|---|
| **1** | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | c) Machine Learning Methods for Engineers | Lecture/ 2 SWS | 25 h | 50 h | 3 |
| | d) Machine Learning Methods for Engineers | Tutorial/ 2 SWS | 25 h | 50 h | 2 |
| **2** | **Language**<br>English | | | | |
| **3** | **Content**<br>Element 1<br>Description of the main challenges that arise when dealing with large data sets and presentations of different possibilities for data management, data cleaning and outlier detection. Basic definitions in artificial intelligence and machine learning: training, validation, backpropagation, loss functions, error metrics. Description of different machine learning-methods (linear and nonlinear regression, gaussian processes, clustering, neural networks, …) and their classification into different categories such as supervised vs. unsupervised, regression vs. classification. Usage of tools to efficiently implement machine learning-methods. Interpretation and analysis of the results and presentation of the potential of machine learning with examples of the chemical and biochemical engineering field.<br><br>**Literature:**<br>The slides of the course and any additional materials such as literature lists and website recommendations will be published in the virtual workrooms in Moodle provided for this purpose. Details will be announced at the beginning of the course. | | | | |
| **4** | **Competencies**<br>The students can analyze the quality of data sets and perform simple operations to clean and prepare the data for the application of different machine learning techniques. The students are able to design and apply several machine learning techniques using efficient software tools and they are able to transfer this knowledge to solve practical problems. The students can recognize reliable results from the application of the presented machine learning techniques and critically evaluate their limitations. | | | | |
| **5** | **Examination Requirements**<br>Oral (max. 30 minutes) or written (90 minutes) + Computer-based project and presentation of 10 minutes | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Basic knowledge of linear algebra. Basic programming knowledge. | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics; Field of study: Process Automation, Robotics, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. Sergio Lucia/* Prof. Dr.-Ing. Sergio Lucia | | | | |

## OPTIMAL POWER FLOW PROBLEMS — ETIT-233

| Rota | Duration | Semester | CP | Workload Presence | Workload Self Study |
|---|---|---|---|---|---|
| Jährlich zum SoSe | 1 Semester oder Block | 2. Semester | 5 | 35 h | 115 h |

**1 Modul structure**

| Nr. | Element | LSF-Nr. | Type | SWS |
|---|---|---|---|---|
| 1 | Optimal Power Flow Problems Vorlesung | 08 XXXX | V | 2 |
| 2 | Optimal Power Flow Problems Übung | 08 XXXX | Ü | 1 |

**2 Language**

Englisch

**3 Content**

Das Problem des optimalen Lastflusses (engl. Optimal Power Flow (OPF)) in Energienetzen tritt in mannigfaltigen Formulierungen und Varianten in der Energietechnik auf. In diesem Kontext bietet die Vorlesung eine Einführung in unterschiedliche Aspekte von OPF Problemen. Es werden die folgenden Themenkomplexe behandelt:

- Formulierung des OPF Problems in AC
- Konvexe Approximationen des OPF Problems
- Stochastische Formulierungen des AC OPF Problems
- Dynamische Formulierungen des OPF Problems für Transport- und Verteilnetzen unter Berücksichtigung von Speicherdynamik
- Verteilte Formulierungen des OPF Problems
- Ausblick auf Ansätze zur Kopplung von elektrischen Netzen und Gasnetzen

Die Lösung wird praktisch mit Hilfe von Standardsoftware (bspw. Matpower oder Pandapower, powermodels.jl) erprobt.

**Literature**

Frank, Stephen, Ingrida Steponavice, and Steffen Rebennack. "Optimal power flow: a bibliographic survey I." Energy systems 3.3 (2012): 221-258.
Frank, Stephen, Ingrida Steponavice, and Steffen Rebennack. "Optimal power flow: a bibliographic survey II." Energy systems 3.3 (2012): 259-289.
Capitanescu, Florin. "Critical review of recent advances and further developments needed in AC optimal power flow." Electric Power Systems Research 136 (2016): 57-68.
Faulwasser, Timm, Alexander Engelmann, Tillmann Mühlpfordt, and Veit Hagenmeyer. "Optimal power flow: an introduction to predictive, distributed and stochastic control challenges." at-Automatisierungstechnik 66, no. 7 (2018): 573-589.

**4 Competencies**

Nach erfolgreicher Teilnahme am Modul besitzen die Studierenden grundlegende Kenntnisse zur Formulierung und Lösung von OPF Problemen. Insbesondere sind sie in der Lage die verschiedenen Arten von OPF Problemen zu erkennen, zu formulieren und mit Hilfe geeigneter Software-Werkzeuge zu lösen.
Anhand praxis-naher Beispiele haben die Studierenden darüber hinaus einen Einblick in die vielfältigen Anwendungsmöglichkeiten des OPF Problems in der Energietechnik erlangt.

**5 Examination Requirements**

*Teilleistungen:*

- Klausur (90 Minuten) oder mündliche Prüfung (max. 30 Minuten)
- vorlesungsbegleitende Projektarbeit mit schriftlichem Bericht*

* Die Gesamtnote wird aus dem arithmetischen Mittel der Teilnoten gebildet. Die genauen Prüfungsmodalitäten werden spätestens zur 2. Veranstaltung bekannt gegeben.

**6 Formality of Examination**

☐ Modulprüfung ☒ Teilleistungen

| | | |
|---|---|---|
| **7** | **Module Requirements (Prerequisites)**<br>Empfohlene Voraussetzungen: Vorkenntnisse zu Grundlagen der elektrischen Energietechnik<br><br>Die Anzahl der Teilnehmerinnen und Teilnehmer ist auf 25 begrenzt. Die Zulassung zur Teilnahme erfolgt gem. § 9 der Prüfungsordnung. | |
| **8** | **Allocation to Curriculum**<br>Wahlpflichtmodul im Masterstudiengang „Elektrotechnik und Informationstechnik“, Studienschwerpunkte „Elektrische Energietechnik“ und „Robotik und Automotive“.<br>Wahlpflichtmodul im Masterstudiengang Automation and Robotics, Schwerpunkte Process Automation, Robotics | |
| **9** | **Responsibility/ Lecturer**<br>Prof. Dr.-Ing. Timm Faulwasser | **Faculty**<br>Fakultät für Elektrotechnik und Informationstechnik |

| **Mobile Radio Networks 1: Fundamentals and Design Aspects** | | | | | **AR-234** |
|---|---|---|---|---|---|
| **Rota**<br>anually SoSe | **Duration**<br>1 Semester | **Semester**<br>2nd | **Credits**<br>5 | **Presence**<br>35 h | **Self-Study Load**<br>115 h |

**1 Module Structure**

| No. | Element / Course | LSF-No. | Type | SWS |
|---|---|---|---|---|
| 1 | Mobile Radio Networks 1: Fundamentals and Design Aspects: Lecture | 08 0104 | V | 2 |
| 2 | Mobile Radio Networks 1: Fundamentals and Design Aspects: Lab Course | 08 0105 | P | 1 |

**2 Language**

English

**3 Content**

1. Market aspects and historical development of mobile communications
2. System aspects (characteristics of propagation, subscriber mobility, resource demand and spectrum allocation, network planning, protocols)
3. TDMA- und CDMA-based cellular networks (2G GSM/GPRS/EDGE, 3G UMTS/HSPA)
4. System architecture of OFDMA-based cellular networks (4G LTE)

The discussion of theoretical content is complemented by practical demonstrations and by case studies on ongoing research and business aspects of mobile radio networks.

**Literature** (respective latest version)

Walke, B.: Mobile Radio Networks, Wiley

Rappaport, Theodore S. Wireless communications: principles and practice. Prentice Hall.

Dahlmann, E.; Parkvall, S.; Sköld, J.: 4G: LTE/LTE-Advanced for Mobile Broadband, Academic Press

**4 Competencies**

After successful completion of the module, students understand the system architectures, protocols, dimensioning and operation of mobile radio networks. Students are able to evaluate the possibilities and challenges of using wireless networks in different deployment environments and fields of application, and to make a technically sound selection. In this way, they acquire the competence to attend more advanced courses or to study more advanced topics for themselves.

**5 Examination**

*Module exam: oral exam (max. 40 minutes) or written exam (max. 180 minutes)**

*Course work: successful completion of lab tasks*

*The exact examination modalities will be announced by the 2nd event at the latest.

**6 Forms of examination and performance**

☒ *Module exam* ☐ Part of modular exam

**7 Participation requirements**

None. Basic knowledge of digital communications and electromagnetic wave propagation is recommended.

**8 Module type and usability of the module**

Mandatory Elective Course in Master Degree Program „Electrical Engineering and Information Technology“, Major „Information and Communications Engineering“.

Elective Class in Master Degree Program „Industrial Engineering“, recommended in major „Information Technology“, module reference number: MB-.

Elective Class in Master Degree Program „Automation & Robotics”, recommended in major „Cognitive Systems”, module reference number: AR-233.

Elective Class in Master Degree Program „Applied Computer Science” and „Computer Science”, both with application subject „Electrical Engineering”, module reference number: INF-MSc-AF-ET-230.

| **9** | **Module Supervisor** | **Faculty in Charge** |
|---|---|---|
| | Prof. Dr.-Ing. Christian Wietfeld | Faculty of Electrical Engineering and Information Technology |

<table>
<tr><th colspan="6">Mobile Radio Networks 2: Advanced Network Concepts — AR-235</th></tr>
<tr><td>Rota<br>anually SoSe</td><td>Duration<br>1 Semester</td><td>Semester<br>2nd</td><td>Credits<br>5</td><td>Presence<br>35 h</td><td>Self-Study Load<br>115 h</td></tr>
<tr><td>1</td><td colspan="5">Module Structure
<table>
<tr><th>No.</th><th>Element / Course</th><th>LSF-No.</th><th>Type</th><th>SWS</th></tr>
<tr><td>1</td><td>Mobile Radio Networks 2: Advanced Network Concepts: Lecture</td><td>XXX</td><td>V</td><td>2</td></tr>
<tr><td>2</td><td>Mobile Radio Networks 2: Advanced Network Concepts: Lab Course</td><td>XXX</td><td>P</td><td>1</td></tr>
</table></td></tr>
<tr><td>2</td><td colspan="5">Language<br>English</td></tr>
<tr><td>3</td><td colspan="5">Content<br>1. Local radio networks (WLAN/Wi-Fi, WPAN, Mesh, DECT)<br>2. Wireless Internet of Things networks (Low Power Wide Area Networks, Cellular-IoT)<br>3. Advanced features of 4G and 5G networks (Carrier Aggregation, Device-to-Device, Network Slicing, Beamforming, Ultra Reliable and Low Latency Communications)<br>4. Satellite networks, Aerial Wireless Networks<br>5. Future mobile network concepts for 5G-Advanced and 6G (e.g. mmWave/THz spectrum, Reflective Intelligent Surfaces, Integration of Artificial Intelligence)<br><br>The discussion of theoretical content is complemented by practical demonstrations and by case studies on ongoing research and business aspects of mobile radio networks.<br><br>Literature (respective latest version)<br>Liberg, Olof, et al. Cellular Internet of Things: From Massive Deployments to Critical 5G Applications. Academic Press, 2019.<br>Dahlmann, E.; Parkvall, S.; Sköld, J.: 4G: LTE/LTE-Advanced for Mobile Broadband, Academic Press<br>P. Marsch, A. Osseiran, J.F. Monserrat, 5G Mobile and Wireless Communications Technology, Cambridge University Press</td></tr>
<tr><td>4</td><td colspan="5">Competencies<br>Upon successful completion of the module, students understand advanced and upcoming mobile radio network concepts and terminology which enables them to characterize research-related challenges of integrating the considered features, assess the feasibility, and to develop design solutions according to design goals. Students further deepen their knowledge base on specific network designs for particular fields of application, and to make a technically sound selection.</td></tr>
<tr><td>5</td><td colspan="5">Examination<br>Module exam: oral exam (max. 40 minutes) or written exam (max. 180 minutes)*<br>Course work: successful completion of lab tasks<br>*The exact examination modalities will be announced by the 2nd event at the latest.</td></tr>
<tr><td>6</td><td colspan="5">Forms of examination and performance<br>☒ Module exam ☐ Part of modular exam</td></tr>
<tr><td>7</td><td colspan="5">Participation requirements<br>None. Basic knowledge of mobile radio networks is recommended.</td></tr>
<tr><td>8</td><td colspan="5">Module type and usability of the module<br>Mandatory Elective Course in Master Degree Program „Electrical Engineering and Information Technology“, Major „Information and Communications Engineering“.<br>Elective Class in Master Degree Program „Industrial Engineering“, recommended in major „Information Technology“, module reference number: MB-.<br>Elective Class in Master Degree Program „Automation & Robotics”, recommended in major „Cognitive Systems”, module reference number: AR-235 .<br>Elective Class in Master Degree Programs „Applied Computer Science” and „Computer Science”, both with application subject „Electrical Engineering”, module reference number: INF-MSc-AF-ET-263.</td></tr>
<tr><td>9</td><td colspan="2">Module Supervisor<br>Prof. Dr.-Ing. Christian Wietfeld</td><td colspan="3">Faculty in Charge<br>Faculty of Electrical Engineering and Information Technology</td></tr>
</table>

| **EMBEDDED AUTONOMY** | | | | | **AR-236** |
|---|---|---|---|---|---|
| **Turnus**<br>Jährlich zumSoSe | **Dauer**<br>1 Semester oder Block | **Studienabschnitt**<br>2. Semester | **LP**<br>10 | **Präsenzanteil**<br>70 h | **Eigenstudium**<br>230 h |

| | | | | | |
|---|---|---|---|---|---|
| 1 | **Modulstruktur** | | | | |
| | **Nr.** | **Element / Lehrveranstaltung** | **LSF-Nr.** | **Typ** | **SWS** |
| | 1 | Embedded Autonomy Vorlesung | 08 XXXX | V | 3 |
| | 2 | Embedded Autonomy Übung | 08 XXXX | Ü | 1 |
| | 3 | Embedded Autonomy Praktikum | 08 XXXX | P | 2 |

**2 Lehrveranstaltungssprache**

Englisch

**3 Lehrinhalte**

- Requirements on functional safety
- Providing and preserving trustworthiness in Autonomous Systems
- System Architectures and Platforms for Autonomous Systems
- Verification of Autonomous Systems

**Literatur**

Christopher Rouff. “Autonomous and Autonomic Systems: With Applications to NASA Intelligent Spacecraft Operations and Exploration Systems” (NASA Monographs in Systems and Software Engineering). Springer-Verlag, Berlin, Heidelberg, 2007.
Samuel Kounev, Jeffrey O. Kephart, Aleksandar Milenkoski, and Xiaoyun Zhu. „Self-Aware Computing Systems”. Springer Publishing Company, Incorporated, 1st edition, 2017.
Defense Advanced Research Projects Agency (DARPA). Broad Agency Announcement - Assured Autonomy, August 2017
Selma Saidi, Dirk Ziegenbein, Jyotirmoy V. Deshmukh, Rolf Ernst: : “Autonomous Systems Design: Charting a New Discipline”, IEEE Design and Test Magazine 2021.

**4 Kompetenzen**

With the successful participation in the module, students will gain basic knowledge in the platforms used in autonomous systems as well as very recent fields required to the design of safe autonomous systems considering functional and non-functional aspects (e.g., safety, reliability).
During the practical exercises to the lecture the students will learn to implement simple autonomous systems tasks (Sensor fusion and AI computation which pose special demands on the architectures in order to implement the Percieve - Decide - Act loop) on embedded platforms. The students will be able to balance the performance limitations of the platform against the complexity of tasks and therefore find an optimal utilization of the resources.

**5 Prüfungen**

*Teilleistungen:*

1. mündliche Prüfung (30 Minuten) oder Klausur (90 Minuten) und
2. vorlesungsbegleitende Projektarbeit mit schriftlichem Bericht *
3. Erfolgreiche Teilnahme an Element 3

* Die Gesamtnote wird aus dem arithmetischen Mittel der Teilnoten von Teilleistung 1 und 2 gebildet.
Die genauen Prüfungsmodalitäten werden spätestens zur 2. Veranstaltung bekannt gegeben.

**6 Prüfungsformen und –leistungen**

☐ Modulprüfung ☒ Teilleistungen

| | | |
|---|---|---|
| 7 | **Teilnahmevoraussetzungen**<br>keine | |
| 8 | **Modultyp und Verwendbarkeit des Moduls**<br>Wahlpflichtmodul im Masterstudiengang "Elektrotechnik und Informationstechnik", Studienschwerpunkte „Informations- und Kommunikationstechnik" und „Mikrosystemtechnik und Mikroelektronik".<br>Wahlpflichtmodul im Masterstudiengang Automation and Robotics, Major Field of Study: Robotics, Cognitive Systems | |
| 9 | **Modulbeauftragte/r**<br>Prof. Dr.-Ing. Selma Saidi | **Zuständige Fakultät**<br>Fakultät für Elektrotechnik und Informationstechnik |

<table>
<tr><th colspan="6">Automotive Systems</th><th>AR-237</th></tr>
<tr><td colspan="2">Rota<br>annually SS</td><td>Duration<br>1 Semester</td><td>Semester<br>2nd (Semester)</td><td>SWS<br>3 SWS</td><td>Credit Points<br>5</td><td>Workload<br>150 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>Credits</td></tr>
<tr><td colspan="2">a) Automotive Systems (AS)</td><td>Lecture/ 2 SWS</td><td>22.5 h</td><td>75 h</td><td>3</td></tr>
<tr><td colspan="2">b) Automotive Systems (AS)</td><td>Tutorial/ 1 SWS</td><td>12.5 h</td><td>40 h</td><td>2</td></tr>
<tr><td>2</td><td colspan="6">Language<br>English</td></tr>
<tr><td>3</td><td colspan="6">Content<br>1. Vehicle dynamics (tires, longitudinal and lateral dynamics)<br>2. Actuators in the mechatronic vehicle (steering, braking, and powertrain systems)<br>3. (Kinematic) vehicle models<br>4. Sensors measuring vehicle internal quantities (acceleration, yaw rate, steering angle, steering torque, wheel speed, sensor data processing)<br>5. Vehicle dynamics systems (braking and driving slip control systems)<br>6. Modern headlight systems and light engineering<br>Literature:<br>- R. Rajamani: Vehicle Dynamics and Control (Springer)<br>- U. Kiencke, L. Nielsen: Automotive Control Systems (Springer)</td></tr>
<tr><td>4</td><td colspan="6">Goals<br>The students acquire a profound knowledge of vehicle dynamics systems (dynamics, sensors measuring vehicle dynamics quantities, actuators, models, simulation, control, and optimization). They are able to understand and solve tasks on vehicle dynamics systems with appropriate methods.</td></tr>
<tr><td>5</td><td colspan="6">Requirements<br>- written exam</td></tr>
<tr><td>6</td><td colspan="6">Forms of examination and performance<br>☒ Module exam ☐ Part of modular exam</td></tr>
<tr><td>7</td><td colspan="6">Participation requirements<br>None.</td></tr>
<tr><td>8</td><td colspan="6">Allocation to Curriculum:<br>Programme: Automation & Robotics, Field of study: Robotics, Cognitive Systems</td></tr>
<tr><td>9</td><td colspan="6">Responsibility/ Lecturer<br>Prof. Dr.-Ing. Prof. h.c. Dr. h.c. Torsten Bertram</td></tr>
</table>

# 3. Semester

| **Advanced Process Control** | | | | | **AR-301** |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>3rd (Semester) | **SWS**<br>4 SWS | **Credit Points**<br>5 | **Workload**<br>150 h |

| | | | | | |
|---|---|---|---|---|---|
| **1** | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Advanced Process Control (APC) | Lecture / 2 SWS | 30 h | 60 h | 3 |
| | b) Advanced Process Control (APC) | Tutorial / 2 SWS | 30 h | 30 h | 2 |
| **2** | **Language**<br>English | | | | |
| **3** | **Content**<br>1. Summary of the analysis of linear dynamic systems: Stability, controllability, observability observability. Stability of nonlinear systems using Lyapunov theory and summary of nonlinear control design methods.<br>2. State estimation for linear and nonlinear systems: Kalman Filter, Extended Kalman Filter, Particle Filter, Mov-ing Horizon Estimation.<br>3. Advanced model-predictive control: linear and nonlinear model predictive control, robust model predictive control, learning-based model predictive control.<br>4. Efficient implementation of model predictive control.<br><br>**Literature:**<br>• Slides<br>• Lecture Notes | | | | |
| **4** | **Competencies**<br>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**<br>The final exam will be an oral (max. 30 minutes) or written (2 hours) exam, depending on the number of participants (form will be announced second week of course).<br>Active participation and collaboration in 75% of computer exercises is mandatory. The students can acquire 15% additional bonus point doing a small controller design project. | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Basic knowledge of dynamic systems and control, as e.g. provided by the course Control Theory and Applications. | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Process Automation Robotics, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr. S. Lucia/* Prof. Dr. S. Lucia | | | | |

| Computational Intelligence | | | | | AR-306 |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>3rd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>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. After a brief introduction with reference to the biological paradigm, the foundations for neural networks are laid with an introduction to threshold logic. Then, traditional single- and multi-layer perceptrons as well as modern deep learning architectures such as convolutional and recurrent neural networks are covered. Various training algorithms are discussed. The content is presented in a way that focuses on the practical and implementation aspects as well as theoretical considerations such as limitation 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.
- Ian Goodfellow, Yoshua Bengio, and Aaron Courville: Deep Learning. MIT Press 2017.
- 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:**<br>Program: Automation & Robotics, Field of study: Robotics, Process Automation, Cognitive Systems |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr. G. Rudolph/* Prof. Dr. G. Rudolph |

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

| | | | | | |
|---|---|---|---|---|---|
| **1** | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Mathematical Simula-tion Techniques (MST) | Lecture/ 2 SWS | 25 h | 65 h | 3 |
| | b) Mathematical Simula-tion 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 department/* Lecturers of the Mathematics department

| Batch Process Operation | | | | | AR-311 |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>3rd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>150h |

| | | | | | |
|---|---|---|---|---|---|
| **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 | 45 h | 2 |
| **2** | **Language**<br>English | | | | |
| **3** | **Content**<br>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.<br><br>**Literature:**<br>• Handouts<br>• Slides | | | | |
| **4** | **Competencies**<br>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**<br>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**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Basic knowledge of mathematical modeling, dynamic systems, and control, as e.g. provided by the course Control Theory and Applications. | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Process Automation | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr. S. Lucia/* Prof. Dr. Stefan Krämer | | | | |

| Process Performance Optimization | | | | | AR-312 |
|---|---|---|---|---|---|
| **Rota** annually WS | **Duration** 1 Semester | **Semester** 3rd (Semester) | **SWS** 4 SWS | **Credit Points** 5 | **Workload** 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:

1. Selection of controllers and control structures
2. Tuning of standard controllers
3. Optimization of the operating conditions by linear programming and nonlinear optimization
4. Model predictive control
5. Batch trajectory optimization
6. Model-based estimation of process variables for monitoring and control
7. Process performance monitoring
8. Dynamic simulation and operator training systems
9. Manufacturing Execution Systems
10. Statistical Process Control, Six Sigma
11. 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)**

This module is mutually exclusive with the module “Process Optimization” 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. Lucia /* Prof. Dr. S. Lucia / Dr. G. Dünnebier (Bayer Technology Services GmbH)

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

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|---|---|---|---|---|---|
| **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**<br>English | | | | |
| **3** | **Content**<br>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.<br><br>**Literature:**<br>• Slides | | | | |
| **4** | **Competencies**<br>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**<br>The final exam will be an oral exam. | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Required knowledge: Solid knowledge of embedded systems, basic knowledge of Operating Systems and C Programming | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study:Robotics, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr. J. Chen/* Prof. Dr. J. Chen | | | | |

| **Online Problems** | | | | | **AR-316** |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>3rd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>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**<br>English | | | | |
| **3** | **Content**<br>1. Competitive Analysis<br>2. Randomized Algorithms<br>3. Deterministic Algorithms<br>4. Game-Theoretic Foundations<br>5. Request-Answer Games<br><br>**Literature:**<br>• Allan Borodin, Ran El-Yaniv, ONLINE COMPUTATION AND COMPETITIVE ANALYSIS. Cambridge University Press. | | | | |
| **4** | **Competencies**<br>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**<br>Oral exam (40 min) | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>Recommended: knowledge in discrete mathematics and foundations of algorithms | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study:Robotics, Cognitive Systems | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. Uwe Schwiegelshohn/* Prof. Dr.-Ing. Uwe Schwiegelshohn | | | | |

| Nonlinear Model Predictive Control – Theory and Applications | | | | | AR-318 |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester | **Semester**<br>3rd (Semester) | **SWS**<br>5 SWS | **Credit Points**<br>10 | **Workload**<br>300 h |

**1 Modul Structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self Study | Credit Points |
|---|---|---|---|---|
| c) Nonlinear Model Predictive Control – Theory and Applications | Lecture/ 3 SWS | 35 h | 40 h | |
| d) Nonlinear Model Predictive Control – Theory and Applications | Tutorial/ 1 SWS | 15 h | 40 h | |
| e) Nonlinear Model Predictive Control – Theory and Applications | Practical training / 1 SWS | | | |

**2 Language**

English

**3 Content**

Elemente1

1. Basics of optimal control theory and numerical optimal control
    a. Optimality condtions for static problems
    b. Formulation of optimal control problems
    c. Gateaux derivative
    d. Pontryagin Maximum Principle
    e. Indirect and direct solution methodsffiiziente derivative computation
2. Advanced aspects of optimal control
    a. Existence of optimal solutions
    b. Dual variables
    c. Singular problems
    d. Dissipativity and turnpike properties
3. Modell predictive control of sampled-data systems
    a. Basics of MPC
    b. Sufficient stability conditions with and without terminal constraints
    c. Economic cost functions
    d. Differences of continuous time and discrete time formulations
    e. Design and implementation aspects
4. Outlook
    a. Stochastic and robust MPC
    b. Limits of MPC
5. Case studies
    a. Energy efficiency in technical systems, multi-energy systems, and others
6. Elemente 2 und 3
7. 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.<br>The students are able to design predictive controllers for nonlinear systems and to validate them by means of simulation. |
| **5** | **Examination Requirements**<br>Project* oral exam (max. 30 minutes) **<br>* Elaboration of a project (Simulation and optimization, 50h) and documentation of the results in report form (ca. 20 pages DIN A4)<br>** The exact examination arrangements will be announced in the second week of the course. |
| **6** | **Formality of Examination**<br>☐ Module Finals ☒ Accumulated Grade |
| **7** | **Module Requirements (Prerequisites)**<br>Necessary Requirements:<br>• Basics of control engineering (state space description, LQR control, Lyapunov functions)<br>• Basics of ordinary differential equations<br>Recommended Requirements:<br>• Basic of optimization, Multivariate Control and Optimal Control |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Robotics, Process Automation, Cognitive Systems |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. Timm Faulwasser/* Prof. Dr.-Ing. Timm Faulwasser |

## Mobile and Pervasive Computing — AR-319

| Rota | Duration | Semester | SWS | Credit Points | Workload |
|---|---|---|---|---|---|
| annually WS | 1 Semester | 3rd (Semester) | 4 SWS | 6 | 180 h |

**1 Modul Structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self Study | Credit Points |
|---|---|---|---|---|
| f) Mobile and Pervasive Computing (MPC) | Lecture/ 2 SWS | 25 h | 65h | 3 |
| g) Mobile and Pervasive Computing (MPC) | Seminar/ 2 SWS | 25 h | 65 h | 3 |

**2 Language**

English

**3 Content**

As advanced sensing and communication technologies have been rapidly developed, mobile and pervasive computing technologies have been paid a lot of attention to enable intelligent services in our daily life. These services provide new insights into unstructured and uncertain information from a variety of data sources in sensor-rich environments and mobile devices. The lecture covers theoretical fundamentals in sensing and computing techniques, how to apply them in practical systems, and design principles in mobile and pervasive computing techniques. The content includes the following topics:

- Wireless perception and computing: active and passive wireless sensing techniques, wireless-based localization, wireless-based mobility analytics, wireless-based activity recognition, and applications based on wireless signals.
- Visual & acoustic perception and computing technologies: Visual-based and acoustic-based localization, image registration, and mobility analytics based on visual and acoustic information.
- Mobile sensing and computing: mobile crowdsourcing in smart cities, privacy-preserving sensing techniques for mobile devices, multi-modal data fusion techniques based on smart devices.
- Edge computing and software-defined computing framework: computation task offloading techniques for low-latency and real-time services, service-oriented/user-centric dynamic computing flows among mobile devices, edge devices, and Cloud.

**Literature:**

Books:

- Minyi Guo, Jingyu Zhou, Feilong Tang, and Yao Shen, "Pervasive Computing: Concepts, Technologies and Applications", Published by CRC Press, 2020.
- Mohammad S. Obaidat, Mieso Denko, and Isaac Woungang, "Pervasive Computing and Networking", published by Wiley, 2011.
- Sherali Zeadally (Editor), Nafaâ Jabeur (Editor), "Cyber-Physical System Design with Sensor Networking Technologies", IET Press in London, England, 2015.

Research papers published in areas of mobile computing, pervasive computing, and communication networking e.g. IEEE Percom, IEEE trans. on Mobile Computing, IEEE ICC/WCNC/Globecom/VTC, and ACM/IEEE IPSN.

Slides of all lectures will be available online.

**4 Competencies**

The goal of the lecture is to establish knowledge of the fundamentals, advanced techniques of mobile and pervasive computing. After completing the lecture, students can independently design innovative pervasive computing systems on mobile and smart platforms, decompose dependency between computation modules and software required by applications, and optimize usage of sensing and computing resources in mobile computing systems.

**5 Examination Requirements**

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|---|---|
| | All students need to successfully pass 50% of assignments to be admitted to the final exam. The final exam is an oral exam (30 minutes). |
| **6** | **Formality of Examination**<br>☒ Module Finals ☒ Accumulated Grade |
| **7** | **Module Requirements (Prerequisites)**<br>Recommendations (helpful but not mandatory): knowledge in foundations of algorithms and wireless communications. |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Robotics, Cognitive Systems<br>Program: Electrical Engineering and Information Technology<br>Program: Informatik |
| **9** | **Responsibility/ Lecturer**<br>*Jun.-Prof. Dr. Fang-Jing Wu/* Jun.-Prof. Dr.-Fang-Jing Wu |

| Machine Learning and optimal Control | | | | | AR-320 |
|---|---|---|---|---|---|
| **Rota**<br>annually WS | **Duration**<br>1 Semester or block course | **Semester**<br>3rd (Semester) | **SWS**<br>3 SWS | **Credit Points**<br>5 | **Workload**<br>150 h |

| | | | | | |
|---|---|---|---|---|---|
| 1 | **Modul Structure** | | | | |
| | **Course (Abbreviation)** | **Type/ SWS** | **Presence** | **Self Study** | **Credit Points** |
| | a) Machine Learning and optimal Control | Lecture/ 2 SWS | 25 h | 65h | 3 |
| | b) Machine Learning and optimal Control | Tutorial/ 1 SWS | 15 h | 15 h | 2 |

**2 Language**

English

**3 Content**

Machine Learning (ML) is one of the key technologies of the 21st century; the applications of ML in technical and information technology systems are already ubiquitous. In this context, the lecture offers a system-theoretically and control-technically motivated introduction to different aspects of Machine Learning. Based on the fundamental distinction between unsupervised, supervised and self-reinforcing learning, the following topics are covered:

- Reinforcement learning and its connection to optimal control (especially approaches of the Hamilton-Jacobi-Bellman equation and dynamic programming) and to model-predictive control.
- Formulation on discrete and continuous state spaces
- The formulation of supervised deep learning as an optimal control problem
- Data-driven approaches to model-predictive control for linear systems.

The application of these ML approaches is formally analysed and practically tested with the help of standard software (e.g. Matlab or Python).

**Literature**

Bishop, C. M. Pattern recognition and machine learning. Springer, 2006.
In der Vorlesung zur Verfügung gestellte Forschungsarbeiten

**4 Competencies**

After successful participation in the module, the students have basic knowledge of machine learning methods and their use in control engineering application contexts. In particular, they are able to recognise the different types of learning problems, formulate them and solve them with the help of suitable software tools.

They are able to explain the fundamental relationships between optimal control and self-reinforcing learning. They are also able to formulate problems of supervised deep learning as optimal control.

With regard to the numerical solution, the students are familiar with basic algorithmic structures and procedures so that they can interpret and evaluate solutions from software tools. Using control engineering examples, the students have also gained an insight into the diverse application possibilities of machine learning.

**5 Examination Requirements**

*Modulprüfungen:*

The final exam is a written (90 minutes) or an oral exam (30 minutes).*

* The exact examination modalities will be announced by the 2nd course at the latest.

| | |
|---|---|
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade |
| **7** | **Module Requirements (Prerequisites)**<br>Recommended prerequisites: Prior knowledge of Fundamentals of Optimal Control (LQR) or numerical optimisation; state space representation and difference equations.<br><br>The number of participants is limited to 50.<br>Admission to participation is in accordance with § 9 of the examination regulations. |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics, Field of study: Robotics, Process Automation<br>Program: Electrical Engineering and Information Technology |
| **9** | **Responsibility/ Lecturer**<br>*Prof. Dr.-Ing. Timm Faulwasser* / Prof. Dr.-Ing. Timm Faulwasser |

## Automated Driving — AR-321

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

**1 Modul structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self study | Credits |
|---|---|---|---|---|
| a) Automated Driving (AD) | Lecture/ 2 SWS | 22.5 h | 75 h | 3 |
| b) Automated Driving (AD) | Tutorial/ 1 SWS | 12.5 h | 40 h | 2 |

**2 Language**

English

**3 Content**

1. Exteroceptive sensors (camera, radar, lidar, ultrasonic, sensor fusion)
2. Conidtional, highly, and fully automated driving:
    a. Situation analysis and interaction-aware trajectory prediction
    b. Trajectory planning and coupled prediction and planning
    c. Control concepts to follow a planned trajectory
3. Machine learning in automated driving
4. Driver monitoring and hand-over models

**Literature:**

- I. Goodfellow, Y. Bengio, A. Courville: Deep Learning (MIT Press)
- D. Forsyth, J. Ponce (Ed.): Computer Vision: A Modern Approach (Prentice Hall)
- **selected papers on automated driving, robotics, and deep learning**

**4 Competencies**

The students acquire a profound knowledge of automated driving systems. They are able to understand and solve tasks on perception, prediction, planning, control, and driver modelling with appropriate methods.

**5 Examination Requirements**

- written exam

**6 Formality of Examination**

☒ Module Finals ☐ Accumulated Grade

**7 Module requirements:**

Programme:

**8 Allocation to Curriculum:**

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

**9 Responsibility/ Lecturer**

*Prof. Dr.-Ing. Prof. h.c. Dr. h.c. Torsten Bertram*

## General Education II — AR-372

| Rota | Duration | Semester | SWS | Credit Points | Workload |
|---|---|---|---|---|---|
| SS and WS | 1 Semester | 2nd / 3rd Semester | 4 SWS | 3 | 90 h |

**1 Modul Structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self Study | Credit Points |
|---|---|---|---|---|
| a) Language Class (German as foreign language) | S/ 4 SWS | 45 h | 45 h | 3 |
| b) Foreign Language Class (Native speakers in German) | S/ 4 SWS | 45 h | 45h | 3 |
| c) Presentation Class | S/ 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 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 department of Electrical Engineering and Information Technology*

| Project Group | | | | | AR-380 |
|---|---|---|---|---|---|
| **Rota**<br>SS and WS | **Duration**<br>1 Semester | **Semester**<br>2nd / 3rd Semester | **SWS**<br>4 SWS | **Credit Points**<br>12 | **Workload**<br>360 h |

**1 Modul Structure**

| Course (Abbreviation) | Type/ SWS | Presence | Self Study | Credit Points |
|---|---|---|---|---|
| a) Project Group | Project | 120 h | 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 department of Electrical Engineering and Information Technology*

# 4. Semester

| **Master Thesis** | | | | | **AR-400** |
|---|---|---|---|---|---|
| **Rota**<br>SS and WS | **Duration**<br>1 Semester | **Semester**<br>4th Semester | **SWS**<br>-- SWS | **Credit Points**<br>30 | **Workload**<br>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**<br>English | | | | |
| **3** | **Content**<br>1. Becoming acquainted with an academic task by using specifications<br>2. Analyzing scientific literature, standards and methods<br>3. Developing solution approaches<br>4. Verification and evaluation of the solution approaches<br>5. Selection and implementation of the most suitable approach<br>6. Scientific description of the methods and solutions in written form<br>The scientific subject of the Master Thesis has to correspond to the main subject. | | | | |
| **4** | **Competencies**<br>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**<br>A final talk of the student is the module exam. | | | | |
| **6** | **Formality of Examination**<br>☒ Module Finals ☐ Accumulated Grade | | | | |
| **7** | **Module Requirements (Prerequisites)**<br>The Master Theses cannot be started before receiving 81 credit points within the curriculum of the Master Program.<br>The subject of the Master Thesis has to be assigned to the student`s major field of study. | | | | |
| **8** | **Allocation to Curriculum:**<br>Program: Automation & Robotics | | | | |
| **9** | **Responsibility/ Lecturer**<br>*Dean of the department of Electrical Engineering and Information Technology* | | | | |