UNIVERSITÀ DI TRENTO

MASTER'S DEGREE IN INTELLIGENT MECHATRONICS ENGINEERING – DESCRIPTION OF COURSE CONTENTS

This document provides a concise description of the learning outcomes of the Master's Degree Programme in **Intelligent Mechatronics Engineering**.

PROGRAMME STRUCTURE

The programme consists of a common first year, which provides all students with a shared foundation in mechatronics engineering, followed by a second year organized into four specialization tracks. Each track is designed to develop advanced knowledge and skills in a specific field.

MECHANICS

This track provides advanced knowledge of the design methods used for mechanical industrial products, together with the related modelling, control, testing and validation techniques.

ROBOTICS AND INTELLIGENT VEHICLES

This track focuses on the enabling technologies of advanced robotics and their most innovative applications, ranging from industrial automation to modern measurement techniques, sensor fusion, motion planning and control. It also addresses the design and development of intelligent transportation systems, with particular emphasis on the strategic technologies underpinning modern autonomous and connected vehicles.

SPACE SYSTEMS AND INSTRUMENTS

This track focuses on the design of systems and instruments for space applications through an integrated approach encompassing hardware design and qualification, sensing technologies, onboard data processing systems, and artificial intelligence for space missions.

ELECTRONICS AND SMART ENERGY SYSTEMS

This track provides advanced knowledge in electronics, power systems and intelligent electrical networks for renewable energy integration. It covers microelectronic devices and sensors, hardware for energy conversion and management, smart grids, and intelligent Internet of Things (IoT) solutions.

FIRST YEAR

DIGITAL MANUFACTURING

The course aims to provide students with an understanding of the principles and applications of digitalization in manufacturing systems, with particular emphasis on production automation and the interconnection of heterogeneous systems within the Industry 4.0 paradigm.

AI AND EMBEDDED SYSTEMS

MODULE 1 – EMBEDDED SYSTEMS

MODULE 2 – MECHATRONICS ARTIFICIAL INTELLIGENCE SYSTEMS

The course provides students with the knowledge and skills required to design intelligent mechatronic systems by integrating embedded systems and Artificial Intelligence.

Students will gain expertise in microcontroller architectures, programming techniques, and communication interfaces for real-time applications, together with the fundamentals of Machine Learning and Deep Learning for data analysis.

Particular emphasis is placed on the integration of physics-based models and neural networks. Practical activities enable students to design, implement and evaluate intelligent solutions for advanced mechatronic systems.

MECHATRONIC SYSTEMS ANALYSIS

MODULE 1 – DYNAMICS AND VIBRATION OF MECHATRONIC SYSTEMS

MODULE 2 – MODELING AND SIMULATION OF MECHATRONIC SYSTEMS

The course provides knowledge and practical skills in the dynamic modelling of mechatronic systems in both the time and frequency domains, including the analysis and interpretation of experimental data.

A systems-oriented approach is adopted to develop modular models that can be transferred across different physical domains, enabling the understanding and analysis of complex engineering systems.

Special attention is devoted to the mathematical modelling of complex engineering and multibody systems, including the derivation of governing equations from physical principles and the development of unified, symbolic, multi-domain models for performance analysis and optimization.

The course also covers differential-algebraic equations (DAEs), symbolic manipulation techniques, and numerical integration methods for efficient dynamic simulation, supported by practical engineering applications.

DIGITAL SIGNAL PROCESSING FOR MECHATRONICS

The course provides advanced knowledge and practical skills in digital signal processing algorithms and techniques for measurement and control applications in mechatronic systems.

Upon completion of the course, students will be able to:

- analyse signals in the frequency domain and correctly interpret their spectra;
- describe and analyse the behaviour of linear time-invariant systems in both the time and frequency domains;
- design and implement digital filtering techniques, selecting the most appropriate solution according to the application requirements;
- extract relevant signal features for Machine Learning applications.

NUMERICAL OPTIMIZATION AND OPTIMAL CONTROL FOR DYNAMICAL SYSTEMS

The course provides knowledge and practical skills in computational methods for analysing and solving optimization problems and dynamical systems described by ordinary differential equations (ODEs) and differential-algebraic equations (DAEs), with applications to constrained optimization and optimal control.

The course introduces the theoretical and numerical tools required to model and solve advanced scientific and engineering problems.

Topics include numerical methods for ODEs, with particular attention to stability and convergence, constrained optimization techniques based on Lagrange multipliers and Karush–Kuhn–Tucker (KKT) conditions, and iterative algorithms such as projected gradient and Newton methods.

The analysis of DAEs is also addressed through index reduction and stabilization techniques.

At the end of the course, students will be able to formulate and solve optimal control problems, interpret optimality conditions through Pontryagin's Minimum Principle, and select appropriate numerical methods for their solution.

AUTOMATIC CONTROL

The course provides the fundamental tools for analysing continuous-time and discrete-time dynamical systems, including linear time-invariant and time-varying systems, with an introduction to nonlinear systems and Lyapunov stability theory.

MECHANICAL DESIGN FOR MECHATRONICS

The course aims to provide students with the theoretical knowledge and practical skills required to:

- interpret stress and strain states in mechanical components;
- understand, identify and quantify the failure mechanisms of mechanical parts;
- recognise the fundamental machine elements used in mechanical design;
- size machine components to withstand prescribed loads and deformations while meeting technical specifications;
- address mechanical design problems following a structured engineering methodology, from requirement definition and constraint identification to concept generation and selection of the optimal solution;
- present engineering analyses through professional technical reports that clearly document the methodology and allow qualified engineers to reproduce the results.

DESIGN OF PRECISION SYSTEMS

The course introduces the principles of precision engineering, with particular emphasis on measurement systems and functional design methodologies.

DESIGN METHODS FOR INDUSTRIAL ENGINEERING

The course provides the fundamental principles for planning, managing and implementing the industrial design process throughout the entire product life cycle, from concept development to reuse and recycling.

Students will develop competencies in technical communication and engineering documentation using modern design methodologies. The course also enhances creativity in engineering design, performance assessment and the application of Robust Design principles.

Particular attention is devoted to the integration of product form, materials and manufacturing processes to ensure functional, efficient and industrially viable products that meet engineering requirements.

SECOND YEAR – MECHANICS

ADVANCED MECHANICAL SYSTEMS

The course provides methods and tools for the modelling and analysis of mechanical and multiphysics systems of engineering interest, with particular emphasis on electromechanical and fluidic transducers and actuators.

Systems are considered in a broad sense, including actuation, control, observation and measurement interfaces.

Upon completion of the course, students will be able to develop lumped-parameter and simplified dynamic models for describing system behaviour and evaluating system performance.

MODELING AND DESIGN WITH FINITE ELEMENTS

The course provides advanced knowledge and methodological skills in the numerical modelling of structural mechanics problems using the Finite Element Method (FEM).

The mathematical and variational foundations of FEM are presented together with the formulation of reliable structural models and the critical assessment of simulation accuracy using professional software tools.

Students will learn to develop finite element models for one-, two- and three-dimensional structures by correctly defining modelling assumptions, boundary conditions and material properties. They will also learn to derive stiffness matrices and implement finite element assembly procedures.

Special attention is devoted to element selection, mesh generation and mesh refinement strategies aimed at achieving an optimal balance between computational efficiency and solution accuracy.

Upon completion of the course, students will be able to analyse and interpret simulation results—including displacements, strains and stresses—evaluate convergence and modelling limitations, identify possible sources of error, and communicate modelling methodologies and results effectively through technical reports.

SPACE MECHANISMS AND SPACE SYSTEMS ENGINEERING

The course provides students with the knowledge and skills required to understand spacecraft architecture, system requirements, and the role of mechanisms within space systems.

Students will learn to analyse the interactions among spacecraft subsystems and the interfaces that influence mechanical design.

They will also acquire the ability to design and model space mechanisms while accounting for mission requirements and environmental constraints, as well as to evaluate their dynamic behaviour, vibration response and structural performance.

Finally, the course introduces hardware testing and qualification strategies for space applications, together with reliability assessment and verification methodologies for space mechanisms.

VEHICLE DYNAMICS

The course provides a comprehensive understanding of vehicle dynamics, with emphasis on the development of physical models, numerical simulations and the analysis of experimental data.

Particular attention is devoted to the relationship between modelling, simulation and experimental validation through practical engineering examples and advanced applications.

Students will learn to model vehicle systems and subsystems, analyse their dynamic behaviour, process experimental test data and evaluate vehicle performance for both design and control purposes.

The course also includes practical aspects of experimental testing and concludes with applications to high-performance and racing vehicle dynamics.

RENEWABLE ENERGY CONVERSION SYSTEMS

The course provides students with the knowledge and tools required to analyse the main renewable energy sources and their associated conversion technologies, considering the entire energy conversion chain—from resource assessment to energy conversion devices, control strategies and system integration.

Upon completion of the course, students will be able to evaluate renewable energy resources, understand the operating principles of the main renewable energy converters and assess their behaviour and performance through simplified modelling approaches.

FUNCTIONAL AND SMART MATERIALS

The course introduces the fundamental concepts of functional and smart materials, including an overview of metamaterials.

Students will examine the operating principles of these materials and the influence of microstructure on their physical properties, together with manufacturing technologies, engineering applications and basic design considerations.

Upon completion of the course, students will understand the mechanisms governing functional materials, select the most suitable material for a given engineering application and identify the most appropriate structural configuration.

They will also be able to analyse the operating principles of sensors and actuators, assessing their functionality, limitations, costs and benefits.

SECOND YEAR – ROBOTICS AND INTELLIGENT VEHICLES

DISTRIBUTED ROBOTICS AND PERCEPTION

The course aims to provide students with a comprehensive understanding of distributed estimation and perception systems for multi-robot platforms employed in both industrial and civil applications.

It also addresses the theoretical foundations of distributed control and estimation, including both classical and Artificial Intelligence-based approaches, when applied to networked robotic systems.

Particular emphasis is placed on the design and implementation of distributed estimation algorithms for intelligent autonomous systems.

SMART SENSING FOR ROBOTICS AND AUGMENTED REALITY

The course provides knowledge and practical skills in robotic perception and eXtended Reality (XR).

It covers the characteristics of environmental and incremental sensors together with measurement technologies used in mixed reality applications, including tracking systems, motion capture and sensor calibration.

Students will develop competencies in signal processing and sensor fusion techniques, including complementary filtering methods.

The course also introduces software tools such as **Unity (C#)** and **Blender** for augmented reality applications, including mobile platforms.

Finally, students will study mobile robot models and methodologies for calibrating kinematic parameters through experimental procedures and validation protocols.

DYNAMIC ROBOT CONTROL

The course provides the theoretical foundations of robot dynamics and classical control algorithms for robotic systems, together with the principles of Learning from Demonstration (LfD).

Students will also develop practical skills in implementing and validating learning and control algorithms through numerical simulation using the Python programming language.

OPTIMISATION AND LEARNING FOR ROBOT CONTROL

This course focuses on advanced control strategies for robotic systems, with particular emphasis on numerical optimal control and reinforcement learning.

Following an introduction to robot modelling and numerical optimization, students will study a wide range of control techniques, from classical approaches to state-of-the-art learning-based methods.

Theoretical concepts are complemented by extensive simulation activities implemented in Python, enabling students to gain practical experience in algorithm development and validation.

Applications include industrial manipulators, legged robots, aerial robots and wheeled mobile robots.

VEHICLE DYNAMICS

The course provides a comprehensive understanding of vehicle dynamics, focusing on the development of physical models, numerical simulations and experimental data analysis.

Special emphasis is placed on the relationship between modelling, simulation and experimental validation through practical engineering examples and advanced case studies.

Students will learn to model vehicle systems and subsystems, analyse their dynamic behaviour, process experimental data and evaluate vehicle performance for design and control applications.

The course also includes laboratory aspects of experimental testing and concludes with applications to high-performance and racing vehicle dynamics.

INTELLIGENT VEHICLES AND AUTONOMOUS DRIVING

The course provides the fundamental knowledge and engineering skills required to design and implement autonomous driving systems.

It covers the main hardware and software architectures of intelligent vehicles and examines the different levels of driving automation according to the **SAE International classification**.

The course also reviews the evolution of vehicle safety systems, from conventional technologies to Advanced Driver Assistance Systems (ADAS), placing them within their historical and technological context.

Particular attention is devoted to vehicle control algorithms at both the architectural and implementation levels, with emphasis on longitudinal and lateral vehicle control.

Students are also introduced to the principal perception systems employed in autonomous driving, including the sensing technologies that enable environment perception and decision making.

The course is complemented by practical implementation activities, enabling students to apply the acquired knowledge to realistic autonomous driving applications.

SECOND YEAR – SPACE SYSTEMS AND INSTRUMENTS

REMOTE SENSING SYSTEMS AND IMAGE ANALYSIS

The course provides an introduction to remote sensing systems, an interdisciplinary field that integrates telecommunications, electronics, signal processing and computer science, with significant applications in the space economy.

The course examines the main components of remote sensing systems, including satellites, optical and radar sensors, and data transmission systems, together with image acquisition, processing and analysis techniques.

Both fundamental methodologies and advanced approaches to image processing and automatic pattern recognition are covered, including Artificial Intelligence and Machine Learning techniques.

The course also includes case studies based on real-world applications and laboratory activities using remotely sensed data, enabling students to develop practical skills in the analysis and interpretation of images and signals.

SPACECRAFT SENSORS AND INSTRUMENTATION

The course provides the knowledge and methodological tools required to understand and design electronic circuits and sensing subsystems for spacecraft applications.

Topics include analog front-end electronics, sensor modelling and radiation effects, while also addressing concepts that are relevant to a wide range of engineering applications beyond the space sector.

Students will develop competencies in amplifier and filter analysis, noise characterization, electrical modelling of sensors, and the operating principles of technologies such as image sensors, star trackers, sun sensors and LiDAR systems.

Upon completion of the course, students will be able to justify engineering design choices and critically interpret experimental results.

SCIENTIFIC MISSION DESIGN

The course introduces the fundamental principles of scientific space mission design, with particular emphasis on high-energy astrophysics observatories and experimental gravitation missions.

Scientific missions are analysed from the perspective of experimental physics performed in the unique laboratory environment provided by orbital platforms.

The course describes the complete mission design process, from the definition of scientific objectives to their translation into technical requirements and engineering solutions, highlighting the influence of system design choices, operational constraints and risk management strategies.

Through examples drawn from real space missions—including **CSES**, **AMS-02**, **LISA**, and geodesy missions—students gain an understanding of the challenges associated with measurement accuracy, data acquisition and management, and the integration of scientific objectives with engineering design.

The course also introduces selected applications in space physics and satellite geodesy.

SPACE STRUCTURES AND ADVANCED APPLICATIONS

The course provides methods and engineering tools for the preliminary design and verification of space structures, linking the fundamentals of structural mechanics with advanced structural architectures for next-generation space missions.

Particular attention is devoted to deployable, modular and reconfigurable structures, including origami-inspired concepts, highlighting their advantages in terms of compactness, efficiency and reliability.

The course adopts a systems engineering approach driven by mission requirements and the constraints typical of the space sector, such as mass limitations, launch loads and the orbital environment.

Students are also introduced to methodologies for interpreting dynamic and vibration specifications during the structural design process.

AI AND ON-BOARD COMPUTING DESIGN

The course provides the foundations for integrating onboard computing systems into satellites and planetary rovers, enabling spacecraft control, autonomous navigation and onboard data processing.

Realistic application scenarios are examined, including the use of Artificial Intelligence for autonomous decision-making and data analysis.

Students learn to address the constraints imposed by the space environment, such as limited power availability, thermal dissipation and extreme operating conditions.

In addition to the theoretical background, the course develops practical skills in the design, programming and integration of embedded computing systems for future space missions.

SPACE MECHANISMS AND SPACE SYSTEMS ENGINEERING

The course provides students with the knowledge and engineering skills required to understand spacecraft architecture, system requirements and the role of mechanisms within space systems.

Students will learn to analyse interactions among spacecraft subsystems and the interfaces that affect mechanical design decisions.

They will also acquire the ability to design and model space mechanisms while accounting for mission requirements and environmental constraints, and to evaluate their dynamic behaviour, vibration characteristics and structural performance.

Finally, the course introduces testing and qualification strategies for space hardware together with reliability assessment and verification methodologies for space mechanisms.

SECOND YEAR – ELECTRONICS AND SMART ENERGY SYSTEMS

LABORATORY OF INTERNET OF THINGS

The course aims to provide students with the knowledge and practical skills required to design, configure and validate complex Internet of Things (IoT) solutions integrated with advanced Artificial Intelligence functionalities.

Particular emphasis is placed on hardware–software integration and the use of modern development platforms, while analysing the trade-offs among cost, performance and energy consumption.

The course covers the main IoT technologies and platforms, including Machine Learning and Deep Neural Networks, as well as cybersecurity and data encryption techniques.

The programme combines theoretical lectures with laboratory activities, allowing students to develop practical skills in IoT prototyping and the application of Deep Learning techniques.

Upon completion of the course, students will be able to develop intelligent IoT products and services, collaborate effectively in engineering design processes, integrate Artificial Intelligence techniques into IoT applications, select appropriate development tools, and identify the main cybersecurity challenges associated with connected systems.

MICROELECTRONIC DEVICES, SENSORS AND MEMS

The course provides a comprehensive introduction to semiconductor electronic devices and microsensors used in industrial and Information and Communication Technology (ICT) applications, describing their operating principles and manufacturing technologies, including Very Large-Scale Integration (VLSI) and Micro-Electro-Mechanical Systems (MEMS).

The course also introduces software tools for the design and development of electronic devices and sensors, covering both technological and engineering design aspects.

Upon completion of the course, students will be familiar with the terminology and key challenges of the field, understand the operating principles of the devices studied, and be able to solve basic numerical and design problems using Technology Computer-Aided Design (TCAD) simulation tools.

ELECTRONICS AND INSTRUMENTATION FOR POWER SYSTEMS

The course provides advanced knowledge and methodological skills concerning the operating principles, design criteria and characterization techniques of power systems for the electrification and power supply of mechatronic equipment.

Upon completion of the course, students will be able to:

- analyse the architecture and design principles of electrical transmission and distribution systems;
- perform and interpret electrical measurements using different types of instrumentation;
- design and compare DC–DC, AC–DC and DC–AC power conversion architectures according to specific application requirements.

SMART GRIDS FOR RENEWABLE ENERGY INTEGRATION

The course introduces the operating principles, modelling methodologies and control strategies of power electronic converters used to interface renewable energy sources and battery energy storage systems with the electrical grid.

Students will gain an understanding of the major challenges associated with the energy transition, including grid stability issues and large-scale blackouts, and will learn how these challenges can be addressed through the advanced control and communication capabilities of modern digital electrical networks, commonly referred to as **smart grids**.

SPACECRAFT SENSORS AND INSTRUMENTATION

The course provides the knowledge and engineering tools required to understand and design electronic circuits and sensing subsystems for spacecraft applications.

Topics include analog front-end electronics, sensor modelling and radiation effects, while also covering concepts relevant to a broad range of engineering applications.

Students will develop competencies in amplifier and filter analysis, noise characterization, electrical modelling of sensors, and the operating principles of technologies such as image sensors, star trackers, sun sensors and LiDAR systems.

Upon completion of the course, students will be able to justify engineering design decisions and critically interpret experimental results.

RENEWABLE ENERGY CONVERSION SYSTEMS

The course provides students with the knowledge and analytical tools required to study the main renewable energy sources and their associated conversion technologies, considering the entire energy conversion chain—from resource assessment to energy conversion devices, control strategies and system integration.

Upon completion of the course, students will be able to evaluate renewable energy resources, understand the operating principles of the main renewable energy conversion systems, and assess their behaviour and performance using simplified analytical models.