COMILLAS UNIVERSIDAD PONTIFICIA ICAI ICADE CIHS

COURSE SYLLABUS 2022-2023

GENERAL INFORMATION

Course information	
Name	Autonomous Mobile Robots
Code	DEA-MIC-526
Main program	Official Master's Degree in Industrial Engineering
Offered in	Máster Universitario en Ingeniería Industrial + Máster en Industria Conectada [2nd year]
Level	Official Master's Degree
Semester	2nd (Spring)
Credits	3.0 ECTS
Type	Elective (MII), Compulsory (MIC)
Department	Electronics, Control and Communications
Coordinator	Jaime Boal Martín-Larrauri

Instructor	
Name	Jaime Boal Martín-Larrauri
Department	Electronics, Control and Communications
Office	D-217 (Alberto Aguilera, 25)
e-mail	jboal@comillas.edu
Phone	91.542.28.00 – Ext. 2742
Office hours	Arrange an appointment through email.
Lab instructor	
Name	María Teresa Álvarez Rodríguez
Department	Electronics, Control and Communications
e-mail	mtalvarez@comillas.edu
Office hours	Arrange an appointment through email.
Lab instructor	
Name	Jaime Pizarroso Gonzalo
Department	Electronics, Control and Communications
e-mail	jpizarroso@comillas.edu
Office hours	Arrange an appointment through email.

COURSE SPECIFIC INFORMATION

Contextualization of the course

Contribution to the professional profile of the degree

Industry 4.0 is fostering collaboration between humans and robots, which must be able to safely share the same workspace. Autonomous mobile robots can operate in an intelligent and orchestrated manner with minimal human intervention to optimize processes, improve flexibility, and enable mass customization. For example, replacing conveyor belts to transport materials around the factory floor while avoiding obstacles, coordinating with their fleet mates, and identifying in real-time where they need to pick up and drop off.

This course is designed as an introductory walk through all the modules that allow a mobile robot to behave autonomously. By the end of the course, students will have well-formed criteria to choose the most appropriate sensors and kinematic configuration for a given application, understand the most common localization and planning algorithms, and have hands-on experience with ROS 2, the de facto standard open-source framework used by researchers and developers around the world to build robotics applications.

Prerequisites

Students willing to take this course should be familiar with linear algebra, basic probability and statistics, control theory, machine learning, and undergraduate-level programming. Previous experience with Python and an object-oriented programming language (especially C++) is also desired although not strictly required.

Competences[1] – Objectives	
Competences – Máster Universitario en Ingeniería Industrial	
General	
BA2.	Be able to apply and integrate their knowledge, understanding, scientific foundation and problem-solving skills in new and imprecisely defined environments, including multidisciplinary contexts both in research and in highly specialized professional fields. *Saber aplicar e integrar sus conocimientos, la comprensión de estos, su fundamentación científica y sus capacidades de resolución de problemas en entornos nuevos y definidos de forma imprecisa, incluyendo contextos de carácter multidisciplinar tanto investigadores como profesionales altamente especializados.*
CG1.	Have adequate knowledge of the scientific and technological aspects of mathematical, analytical, and numerical methods in engineering, electrical engineering, energy engineering, chemical engineering, mechanical engineering, mechanics of continuous media, industrial electronics, automation, manufacturing, materials, quantitative management methods, industrial computing, urban planning, infrastructures, etc. *Tener conocimientos adecuados de los aspectos científicos y tecnológicos de: métodos matemáticos, analíticos y numéricos en la ingeniería, ingeniería eléctrica, ingeniería energética, ingeniería química, ingeniería mecánica, mecánica de medios continuos, electrónica industrial, automática, fabricación, materiales, métodos cuantitativos de gestión, informática industrial, urbanismo, infraestructuras, etc.*
Competences – Máster en Industria Conectada	
General	
CG1.	Have acquired advanced knowledge and demonstrated, in a research and technological or highly specialized context, a detailed and well-founded understanding of the theoretical and practical aspects, as well as of the work methodology in one or more fields of study. *Haber adquirido conocimientos avanzados y demostrado, en un contexto de investigación científica y tecnológica o altamente especializado, una comprensión detallada y fundamentada de los aspectos teóricos y prácticos y de la metodología de trabajo en uno o más campos de estudio.*
CG2.	Know how to apply and integrate their knowledge, understanding, scientific rationale, and problem-solving skills to new and imprecisely defined environments, including highly specialized multidisciplinary research and professional contexts. *Saber aplicar e integrar sus conocimientos, la comprensión de estos, su fundamentación científica y sus capacidades de resolución de problemas en entornos nuevos y definidos de forma imprecisa, incluyendo contextos de carácter multidisciplinar tanto investigadores como profesionales altamente especializados.*
CG5.	Be able to transmit in a clear and unambiguous manner, to specialist and non-specialist audiences, results from scientific and technological research or state-of-the-art innovation, as well as the most relevant foundations that support them. *Saber transmitir de un modo claro y sin ambigüedades, a un público especializado o no, resultados procedentes de la investigación científica y tecnológica o del ámbito de la innovación más avanzada, así como los fundamentos más relevantes sobre los que se sustentan.*
CG6.	Have developed sufficient autonomy to participate in research projects and scientific or technological collaborations within their thematic area, in interdisciplinary contexts and, where appropriate, with a high knowledge transfer component. *Haber desarrollado la autonomía suficiente para participar en proyectos de investigación y colaboraciones científicas o tecnológicas dentro de su ámbito temático, en contextos interdisciplinares y, en su caso, con una alta componente de transferencia del conocimiento.*

[1] Competences in English are a free translation of the official Spanish version.

CG7.	Being able to take responsibility for their own professional development and their specialization in one or more fields of study. *Ser capaces de asumir la responsabilidad de su propio desarrollo profesional y de su especialización en uno o más campos de estudio.*
Specific	
CE6.	Understand the role of mobile robots in the improvement of industrial processes and be able to design and implement software that allows them to behave autonomously. *Comprender el papel de los robots móviles en la mejora de los procesos industriales y ser capaz de diseñar e implementar software que permita que se comporten de forma autónoma.*
Learning outcomes	
RA1.	Differentiate among the sensors and locomotion methods used in robotics and select the most appropriate combination for a given application.
RA2.	Derive the kinematic equations of a wheeled mobile robot.
RA3.	Implement the most common localization algorithms.
RA4.	Understand why when a mobile robot is in an unknown or changing environment it is necessary to estimate its position and build a map simultaneously.
RA5.	Apply path planning and tracking algorithms, including those that allow obstacle avoidance.
RA6.	Understand the structure of the Robot Operating System (ROS) and use it to build robotic software.
RA7.	Assemble all the basic modules that allow a mobile robot to behave autonomously.

CONTENTS

Contents
Theory
Unit 1. Introduction to robotics
1.1 The history of robotics 1.2 Types of robots (industrial manipulators, collaborative robots, wheeled, legged, flying…) 1.3 The see-think-act cycle
Unit 2. Python crash course
2.1 Setup 2.2 Basic syntax 2.3 Collections 2.4 Functions 2.5 Classes
Unit 3. Perception
3.1 Robot sensors (encoders, range sensors, radar, LiDAR, cameras…) 3.2 Fundamentals of computer vision
Unit 4. Wheeled kinematics
4.1 Types of wheels 4.2 Holonomic vs. non-holonomic systems 4.3 Forward and inverse kinematics of a differential drive robot 4.4 Other kinematic configurations (tricycle, Ackermann, robots with omni and Mecanum wheels…)

Unit 5. Robot Operating System (ROS 2)
5.1 What is ROS? 5.2 Graph concepts (nodes, messages, topics) 5.3 Services 5.4 Launch files
Unit 6. Localization
6.1 Histogram filters (Markov localization) 6.2 Kalman filters 6.3 Particle filters (Monte Carlo localization) 6.4 Introduction to SLAM (Simultaneous Localization and Mapping)
Unit 7. Motion planning
7.1 Grid methods: A* 7.2 Roadmap methods: Visibility graphs and generalized Voronoi diagrams (GVD) 7.3 Sampling methods: probabilistic roadmaps (PRM) and rapidly exploring random trees (RRT, RRT*) 7.4 Virtual potential fields
Unit 8. Path tracking
8.1 Follow-the-carrot 8.2 Pure pursuit
Laboratory
Lab 1. Wall following
In the first lab session, students will become familiar with ROS 2 and CoppeliaSim, the robot simulator used throughout the course. They will build a Python application (ROS 2 node) to command a simulated differential drive robot to follow a wall. The goal is to understand the publisher/subscriber mechanism and allow the robot to explore an unknown environment without crashing.
Lab 2. Particle filter localization
The aim of this session is that students improve their understanding of the particle filter algorithm. Building on the previous lab assignment, they will implement a basic particle filter from scratch on a new node that will make the robot localize itself as it safely moves following the walls.
Lab 3. Path planning with A*
In the third lab session, students will implement an A* node to plan the path from a known initial pose to a given destination. The path will be smoothed to make it easier to follow regardless of the robot's kinematics.
Lab 4. Pure pursuit tracking
Finally, students will program a tracking node to follow the smoothed path from the previous session.
Final project
The final project is an integration activity in which every team will bring together and refine all the modules developed during the lab assignments. The simulated robot will start at a random position in a new larger environment, will have to first localize itself within a known map, and then race to reach a given destination. There will be a competition in which extra credit will be awarded.

TEACHING METHODOLOGY

General methodological aspects
Inspired by the "learn by doing" paradigm, this course is designed to provide students with the tools they require to develop a robotics application by the end of the term. In every unit, after the initial explanation of each concept, the instructor will propose individual and group quizzes and activities (some of which will be graded) to test students' understanding. Once they are more confident with the material, they will be asked to implement what they have learned in a lab session where they will start building blocks that will help them advance in their final project.

In-class activities	Competences
▪ **Lectures:** The lecturer will introduce the fundamental concepts of each unit, along with some practical recommendations, and will go through worked examples to support the explanation. Active participation will be encouraged by raising open questions to foster discussion and by proposing online quizzes and short application exercises to be solved in class either on paper or using a software package.	CG1, CG7, CE6
▪ **Lab sessions:** Under the instructor's supervision, students, divided into small groups, will apply the concepts and techniques covered in the lectures to simulated versions of commercial mobile robots.	CG1, CG2, CG5, CG6, CG7, CE6
▪ **Tutoring** for groups or individual students will be organized upon request.	–
Out-of-class activities	**Competences**
▪ Personal study of the course material and resolution of the proposed exercises.	CG1, CG7, CE6
▪ Lab session preparation to make the most of in-class time.	CG1
▪ Lab results analysis and report writing.	CG2, CG5, CE6
▪ Development of a final project in small groups.	CG1, CG2, CG5, CG6, CG7, CE6

STUDENT WORK-TIME SUMMARY

IN-CLASS HOURS			
Lectures		**Lab sessions**	
16		14	
OUT-OF-CLASS HOURS			
Self-study	**Lab preparation**	**Lab report writing**	**Final project**
20	4	12	24
		ECTS credits:	**3.0 (90 hours)**

EVALUATION AND GRADING CRITERIA

Evaluation activities	Grading criteria	Weight
Quizzes	▪ Understanding of the theoretical concepts.	10%
Final exam	▪ Understanding of the theoretical concepts. ▪ Application of these concepts to problem-solving. ▪ Critical analysis of numerical exercises' results.	30%
Lab assignments	▪ Application of theoretical concepts to real problem-solving. ▪ Ability to use and develop robotics software. ▪ Written communication skills.	40%
Final project	▪ Problem analysis. ▪ Quality of the proposed solution. ▪ Teamwork. ▪ Oral presentation skills. ▪ There will be an intra-group evaluation method to differentiate among team members.	20%

Grading

Regular assessment

- **Theory** will account for 40%, of which:
  - Quizzes: 10%
  - Final exam: 30%
- **Lab** will account for the remaining 60%, of which:
  - Lab assignments: 40%
  - Final project: 20%

In order to pass the course, the weighted average mark must be greater or equal to 5 out of 10 points, the mark of the final exam must be greater or equal to 4 out of 10 points, and the laboratory mark (the weighted average of the assignments and the final project) must be at least 5 out of 10 points. Otherwise, the final grade will be the lower of the three marks.

Retake

Lab marks will be preserved as long as the weighted average of the assignments and the final project results in a passing grade. Otherwise, a new project will have to be developed and handed in. In addition, all students will take a final exam. The resulting grade will be computed as follows:

- **Theory** will account for 40%, of which:
  - Quizzes: 10%
  - Final exam: 30%
- **Lab** will account for the remaining 60%, of which:
  - If the student passed the lab during regular assessment
    - Lab assignments: 40%
    - Final project: 20%
  - Otherwise
    - Final project: 60%

As in the regular assessment period, in order to pass the course, the weighted average mark must be greater or equal to 5 out of 10 points, the mark of the final exam must be greater or equal to 4 out of 10 points, and the mark of the laboratory must be at least 5 out of 10 points. Otherwise, the final grade will be the lower of the three marks.

Course rules

- Class attendance is mandatory according to Article 93 of the General Regulations (Reglamento General) of Comillas Pontifical University and Article 6 of the Academic Rules (Normas Académicas) of the ICAI School of Engineering. Not complying with this requirement may have the following consequences:
  - Students who fail to attend more than 15% of the lectures may be denied the right to take the final exam during the regular assessment period.
  - Regarding laboratory, absence to more than 15% of the sessions can result in losing the right to take the final exam of the regular assessment period and the retake. Missed sessions must be made up for credit.
- Students who commit an irregularity in any graded activity will receive a mark of zero in the activity and disciplinary procedures will follow (cf. Article 168 of the General Regulations (Reglamento General) of Comillas Pontifical University).

WORK PLAN AND SCHEDULE[2]

Activities	Date/Periodicity	Deadline
Quizzes	In every lecture	–
Final exam	After the lecture period	–
Lab sessions	Weeks 3 to 6	–
Review and self-study of the concepts covered in the lectures	After each lesson	–
Lab preparation	Before every lab session	–
Lab report writing	–	One week after the end of each session
Final project	From week 3	The date of the final exam

BIBLIOGRAPHY AND RESOURCES

Basic references

- Slides prepared by the lecturer (available in Moodle).
- R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to Autonomous Mobile Robots*, 2nd Ed., MIT Press, 2011. ISBN-13: 978-0-262-01535-6
- S. Thrun, W. Burgard, and D. Fox, *Probabilistic Robotics*, 1st Ed., MIT Press, 2006. ISBN-13: 978-0-262-20162-9
- Robot Operating System (ROS 2), [Online]. Available: https://www.ros.org
- CoppeliaSim, [Online]. Available: https://www.coppeliarobotics.com/

Complementary references

- B. Siciliano and O. Khatib (eds.), *Springer Handbook of Robotics*, 2nd Ed., Springer-Verlag Berlin Heidelberg, 2016. ISBN-13: 978-3-319-32550-7
- P. Corke, *Robotics, Vision and Control: Fundamental Algorithms in MATLAB*, 2nd Ed., Springer International Publishing, 2017. ISBN-13: 978-3-319-54412-0
- R. Szeliski, *Computer Vision: Algorithms and Applications*, 1st Ed., Springer, 2011. ISBN-13: 978-1-848-82934-3
- K. M. Lynch and F. C. Park, *Modern Robotics: Mechanics, Planning and Control*, 1st Ed., Cambridge University Press, 2017. ISBN-13: 978-1-107-15630-2
- S. M. LaValle, *Planning Algorithms*, 1st Ed., Cambridge University Press, 2006. ISBN-13: 978-0-521-86205-9

[2] A detailed work plan of the subject can be found in the course summary sheet (see following page). Nevertheless, this schedule is tentative and may vary to accommodate the rhythm of the class.

	In-class activities				Out-of-class activities				Learning outcomes
Week	Time [h]	Lecture	Laboratory	Assessment	Time [h]	Self-study	Lab preparation and report writing	Other activities	Code
1	2	Course overview (0.5h) Unit 1. Introduction to robotics (0.5h) Unit 2. Python crash course (1h)			1	Review and self-study (1h)			RA1
	2	Unit 2. Python crash course (1h) Unit 3. Perception (1h)		Quiz	1	Review and self-study (1h)			RA1
2	2	Unit 3. Perception (1h) Unit 4. Wheeled kinematics (1h)		Quiz	2	Review and self-study (2h)			RA1, RA2
	2	Unit 5. ROS 2 (2h)		Quiz	2	Review and self-study (2h)			RA6
3	2		Lab 1. Wall following (2h)		4		Lab preparation (1h) Report writing (3h)		RA1, RA2, RA6
	2	Unit 6. Localization (2h)		Quiz	4	Review and self-study (2h)		Final project development (2h)	RA3, RA4
4	2	Unit 6. Localization (2h)		Quiz	2	Review and self-study (2h)			RA3, RA4
	2		Lab 2. Particle filter localization (2h)		4		Lab preparation (1h) Report writing (3h)		RA3, RA6, RA7
5	2	Unit 7. Motion planning (2h)		Quiz	4	Review and self-study (2h)		Final project development (2h)	RA5
	2		Lab 3. Path planning with A* (2h)		4		Lab preparation (1h) Report writing (3h)		RA5, RA6
6	2	Unit 8. Path tracking (2h)			4	Review and self-study (2h)		Final project development (2h)	RA5
	2		Lab 4. Pure pursuit tracking (2h)		4		Lab preparation (1h) Report writing (3h)		RA5, RA6, RA7
7	2		Final project (2h)		6			Final project development (6h)	RA3, RA5, RA6, RA7
	2		Final project (2h)		6			Final project development (6h)	RA3, RA5, RA6, RA7
8	2		Final project (2h)		6			Final project development (6h)	RA3, RA5, RA6, RA7
				Final exam Final project[3]	6	Final exam preparation (6h)			RA1 – RA7

[3] The final exam and the final project presentation will be held the week after the lecture period.