ENG-654

Kinematics grounded motion planning for robots

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Cursus	Sem.	Type
Robotics, Control and Intelligent Systems		Opt.
Robotics	MA1, MA3	Opt.

Language of teaching	English
Credits	4
Session	Winter
Semester	
Exam	During the semester
Workload	120h
Weeks	14
Hours	**4 weekly**
Courses	1.86 weekly
Exercises	.43 weekly
Project	1.71 weekly
Number of positions	**30**

Frequency

Only this year

Remark

Next time: Fall 2026

Summary

Students learn forward/inverse kinematics, singularity analysis, and constraint-aware path planning for modern robotic manipulators, implementing kinematic models and planners in a final project.

Content

The course is worth 4 ECTS credits and includes 56 hours of activities:

- 32 hours of lectures and hands-on exercises
- 24 hours dedicated to a post-lecture project, completed in groups of two
- Each teaching week includes 8 hours of lectures and 8 hours of exercises

Your final evaluation will be based on your project report and an oral presentation. Grades will be awarded on the EPFL scale from 1 to 6.
Schedule:
Monday, 14 September
Wednesday, 16 September
Tuesday, 22 September
Wednesday, 23 September
Morning block:
08:15-09:00
09:15-10:00
10:15-12:15
Afternoon block:
14:00-14:45
15:00-15:45
16:00-18:00
Course Overview:

Most people assume that planning a path from A to B is a solved problem, and that the only remaining challenge is collecting enough data to make robots do household chores. But this is far from the truth. Anyone who has worked on pick-and-place tasks in cluttered environments knows that, despite many available planners, finding and quickly

replanning a safe path, especially when objects are unexpectedly moved, is still a complex and challenging problem. This is mostly due to the fact that robot motions are inherently limited by their kinematics.
Have you ever been astonished to see that year after year, new robot arms enter the market and yet they all look almost identical to existing models? Yet, despite their similar appearance,
these robot arms can differ significantly in their kinematic structure. Moreover, while serial robots dominate industrial applications, parallel robots are still widely used as they offer complementary strengths, such as stiffness, payload capacity, and precision, while introducing unique challenges, particularly in singularity analysis. As a result, tasks carefully programmed or learned on one robot often cannot be directly transferred to another. These differences have real consequences and will hinder large-scale deployment of controllers for industrial and household manipulation tasks.

This course will teach you how to analyze and understand robot kinematics, identify which designs are easier to control, and recognize potential limitations. You will explore not only serial robots, but also parallel architectures, discovering how their singularities differ and how redundancy, whether in actuation or kinematic structure, can be leveraged to enhance performance. With this knowledge, you will not only be able to program robots more effectively, but also advise industry on selecting the right robotic platform for their specific needs.Â The study of redundant parallel robots will also serve as an introduction to physical human-robot interaction with which it presents unexpected similarities.
Specifically, this course will allow you to develop an analytical, intuition-driven understanding of forward and inverse kinematics, singularity visualization, and constraint-aware motion planning (joint limits, collision avoidance, and singularity robustness). We will evaluate this on a variety of platforms, from robotic arms doing complex pick and place, to parallel robots demonstrating unique motion constraints and advantages. At this end of the class, you should be able to confidently explain and predict robot ability to perform a given task, a growing need as modern robots increasingly execute learning-based policies that must still obey geometry.

Content:

The course focuses on analytical treatments of kinematics, forward/inverse kinematics and singularity structure, supported by differential kinematics when needed for interpretation and visualization. Students build models from DH parameters and URDF, study the multiplicity of IK solutions and their continuation along a path, and learn how singularities shape reachable motions and planner robustness. A dedicated section will cover parallel robot modeling, emphasizing their distinct singularity structures, such as forward singularities that do not appear in serial robots. Constraint-aware motion planning is treated as a kinematics problem: selecting consistent IK branches while respecting joint limits, avoiding collisions via robot geometry, and staying away from ill-conditioned regions. The course will also explore redundant parallel robots and their role in enabling adaptive and safe physical interaction. Practical sessions emphasize implementation and validation in realistic robot simulations, culminating in a final project that integrates the full pipeline.

1. Robot modeling for planning: frames, DH parameters, URDF; joint limits and collision geometry
2. Analytical forward and inverse kinematics; multiple IK solutions and solution continuation along a path
3. Singularity analysis and visualization; interpreting what motions are possible near singular configurations
4. Differential kinematics (Jacobian) as a tool for interpretation, conditioning metrics, and robustness analysis
5. Constraint-aware motion planning: joint limits, collision checking, singularity-aware planning and execution in simulation
6. Parallel robot kinematics: modeling, complementary strengths and weaknesses compared to serial robots, and unique singularity analysis
7. Redundant parallel robots: cable-driven parallel robots, actuation and kinematic redundancy, and their applications in physical human-robot interaction
8. Advanced glimpses: screw-theory formulation for compact motion description; an introduction-level view of Conformal Geometric Algebra (CGA) as a modern geometric language
9. Final project: end-to-end kinematics-grounded motion planning pipeline deployed on realistic robot simulations, with evaluation and a concise report.

Note

This course is hands-on and project-oriented. Participants are expected to be comfortable with linear algebra and basic programming in Python and Matlab.
The final project involves implementing and validating kinematics-based, constraint-aware motion planning in realistic robot simulation, including joint limits, collision avoidance, and singularity-robust trajectories.

Keywords

Robot kinematics; forward/inverse kinematics; Jacobian; singularities; multiple IK solutions; multiple FK solutions;

cuspidality/internal singularities; redundant robots; constraint-aware motion planning; joint limits; collision avoidance; robot simulation.

Learning Prerequisites

Required courses

EPFL Courses or equivalent: MICRO-450 Basics of robotics for manipulation

Important concepts to start the course

Linear algebra, multivariable calculus, Rigid-body transformations, Programming in Python

Resources

Websites

- https://www.ieee-ras.org/ras-university/?ras_page=docs/chap1_basic_motion_ctrl/kinematics.html
- http://hhttps://www.ieee-ras.org/ras-university/?ras_page=docs/chap5_adv_kin/01_singularity_analysis.html

Moodle Link

- https://go.epfl.ch/ENG-654