240AR059 - Geometric Fundamentals for Robot Design

Coordinating unit: 240 - ETSEIB - Barcelona School of Industrial Engineering
Teaching unit: 707 - ESAII - Department of Automatic Control
Academic year: 2018
Degree: MASTER'S DEGREE IN AUTOMATIC CONTROL AND ROBOTICS (Syllabus 2012). (Teaching unit Optional)
MASTER'S DEGREE IN INDUSTRIAL ENGINEERING (Syllabus 2014). (Teaching unit Optional)
ECTS credits: 4,5
Teaching languages: English

Teaching staff

Coordinator: Lluís Ros
(http://www.iri.upc.edu/people/ros)
Others: Pablo Jiménez

Opening hours

Consultation hours should be agreed with the professor

Prior skills

Entry-level courses in linear algebra, mechanics, and a working knowledge of MATLAB.

Degree competences to which the subject contributes

Specific:
1. The student will have knowledge to analyze, design and implement advanced robotic applications.

General:
2. Ability to conduct research, development and innovation in the field of systems engineering, control and robotics, and as to direct the development of engineering solutions in new or unfamiliar environments, linking creativity, innovation and transfer of technology
3. Have adequate mathematical skills, analytical, scientific, instrumental, technological, and management information.

Teaching methodology

The web page http://www.iri.upc.edu/gfrd contains the full information of the course.

The subject will be worked out in theory and problem sessions, and with a few practice miniprojects. Depending on the evolution of the course, a number of seminar sessions might be programmed as well. In such sessions, the active participation of the assistants is a fundamental aspect, and the teacher's task is, essentially, to direct the session, presenting and setting the topics in context, and coordinating the debate and the discussion among the students. The course is structured into several modules. Modules 1 to 5 mainly follow the book by Joseph Duffy, "Statics and Kinematics with Applications to Robotics", Cambridge University Press, 1996. Module 6 loosely follows material that can be found in the book by Joseph K. Davidson and Kenneth H. Hunt. "Robots and Screw Theory: Applications of Kinematics and Statics to Robotics". Oxford University Press, 2004. However, some of the modules contain additional material not covered in such books. Lecture notes for all modules will be made available on-line in the course web page.

Learning objectives of the subject
Geometry is essential to many human activities and it is deeply embodied in how humans think. In Robotics, it brings deep insight into the principles of robot motion and control, and develops creativity and intuition, abilities much needed for the proper design and study of robots. A main goal of this course is to get acquainted with such abilities, by way of exploring the geometry of the kinematic and static behavior of robotic mechanisms.

Traditionally, the theories of statics and instantaneous kinematics have been learned separately in mechanical engineering courses. However, they proceed alongside one another, with the important principle of reciprocity linking them together. Using this principle, and the homogeneous representation of forces and velocities as screw vectors, this course aims at studying the two subjects in a unified manner. In this way, the kinetostatic analysis of robots becomes computationally much simpler, and the conclusions derived much richer. Overall, a global picture of the behavior of manipulation devices in and out of singular configurations is gained, which provides important information for robot design.

During the course, the techniques are applied to serial and parallel robots, but also to innovative systems like cable-driven manipulators, flying robots, or multi-robot formations.

**Study load**

<table>
<thead>
<tr>
<th>Total learning time: 112h 30m</th>
<th>Hours medium group:</th>
<th>27h</th>
<th>24.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours small group:</td>
<td>13h 30m</td>
<td>12.00%</td>
<td></td>
</tr>
<tr>
<td>Self study:</td>
<td>72h</td>
<td>64.00%</td>
<td></td>
</tr>
</tbody>
</table>
240AR059 - Geometric Fundamentals for Robot Design

<table>
<thead>
<tr>
<th>Module 1. Mobility and position analysis</th>
<th>Learning time: 10h</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description:</strong></td>
<td>Theory classes: 3h</td>
</tr>
<tr>
<td>1.1 The configuration space of a general multibody system</td>
<td>Practical classes: 1h</td>
</tr>
<tr>
<td>1.2 Mobility analysis and its impact on robot design</td>
<td>Self study: 6h</td>
</tr>
<tr>
<td>Related activities:</td>
<td></td>
</tr>
</tbody>
</table>

**Description:**
1.1 The configuration space of a general multibody system
   - The pose of a link
   - The notion of configuration
   - Joint assembly constraints
   - Implicit representation of the C-space
   - Parametric representation of the C-space

1.2 Mobility analysis and its impact on robot design
   - Intuitive notion of mobility
   - The Gru?bler-Kutzbach criterion
   - Mathematical basis of the criterion
   - Failure of the criterion
   - The criterion works "almost always"

1.3 Position analysis
   - The input and output spaces
   - Kinematic problems
   - Solution approaches
   - Closed-form solutions
   - Constructive geometric methods
   - General methods

**Related activities:**
Lecture and problem sessions, and deliverable miniprojects.
## Module 2. Statics

<table>
<thead>
<tr>
<th>Description:</th>
<th>Related activities:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Plücker coordinates of a line in the XY plane</td>
<td>Lecture and problem sessions, and deliverable miniprojects.</td>
</tr>
<tr>
<td>2.2 The point of intersection of two lines</td>
<td></td>
</tr>
<tr>
<td>2.3 The statics of plane rigid systems</td>
<td></td>
</tr>
<tr>
<td>2.4 Translation and rotation of reference frames</td>
<td></td>
</tr>
<tr>
<td>2.5 Symbolic representation of a wrench</td>
<td></td>
</tr>
<tr>
<td>2.6 Statics of parallel manipulators</td>
<td></td>
</tr>
<tr>
<td>2.7 The geometrical meaning of the inverted Jacobian</td>
<td></td>
</tr>
<tr>
<td>2.8 Singular configurations of a parallel robot</td>
<td></td>
</tr>
</tbody>
</table>

**Learning time:** 18h
- Theory classes: 4h
- Practical classes: 3h
- Self study: 11h

## Module 3. Kinematics

<table>
<thead>
<tr>
<th>Description:</th>
<th>Related activities:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 The coordinates of a vertical line</td>
<td>Lecture and problem sessions, and deliverable exercises.</td>
</tr>
<tr>
<td>3.2 Angular velocities and the instant center</td>
<td></td>
</tr>
<tr>
<td>3.3 The twist as a multiple of a vertical line</td>
<td></td>
</tr>
<tr>
<td>3.4 Pure translations and the line at infinity</td>
<td></td>
</tr>
<tr>
<td>3.5 Ray and axis coordinates</td>
<td></td>
</tr>
<tr>
<td>3.6 Translation and rotation of reference frames</td>
<td></td>
</tr>
<tr>
<td>3.7 Observational frames vs coordinate systems</td>
<td></td>
</tr>
<tr>
<td>3.8 Instantaneous kinematics of serial manipulators</td>
<td></td>
</tr>
<tr>
<td>3.9 Singularities of serial manipulators</td>
<td></td>
</tr>
<tr>
<td>3.10 Singularities of closed kinematic chains</td>
<td></td>
</tr>
</tbody>
</table>

**Learning time:** 18h
- Theory classes: 4h
- Practical classes: 3h
- Self study: 11h
### Module 4. Dualities

**Description:**
- 4.1 Principle of virtual power and reciprocity
- 4.2 Twists of freedom and wrenches of constraint of simple robots
- 4.3 Static analysis and duality diagram of a serial manipulator
- 4.4 Kinematic analysis and duality diagram of a parallel robot
- 4.5 Reciprocal wrench methods and their extensions for general fully-parallel robots

**Related activities:**
Lecture and problem sessions, and deliverable miniprojects.

**Learning time:** 30h
- Theory classes: 8h
- Practical classes: 4h
- Self study: 18h

### Module 5. Hybrid control of force and position in contact situations

**Description:**
- 5.1 Introduction
- 5.2 Controllable positions and force variations in contact situations
- 5.3 Rigidity analysis of compliant 3-RPR mechanisms
- 5.4 The rigidity matrix in a new frame
- 5.5 A hybrid control strategy

**Related activities:**
Lecture and problem sessions, and deliverable miniprojects.

**Learning time:** 16h
- Theory classes: 4h
- Practical classes: 2h
- Self study: 10h

**Appendixes:**
- Appendix A: Infinitesimal displacements
- Appendix B: The displacement equations
- Appendix C: Derivatives and differentiation
- Appendix D: The derivative of a line
Module 6. General twists and wrenches

**Description:**
5.1 Poinsot's theorem and general wrenches
   - A review of the axioms of statics.
   - Reduction operations: The resultant wrench
   - Forces and torques as multiples of lines

5.2 Chasles's theorem and general twists
   - Elementary velocity fields
   - Reduction operations: The equivalent twist
   - Pure rotations and translations as multiples of lines

5.3 Kinetostatics of spatial serial and parallel manipulators
   - Static analysis of serial robots and kinematic analysis of parallel robots
   - Additional relationships through reciprocity

**Related activities:**
Lecture and problem sessions, and deliverable miniprojects.

**Learning time:** 16h
- Theory classes: 4h
- Practical classes: 2h
- Self study: 10h

**Qualification system**
Grading is mainly based on the score obtained in practice mini-projects and in a final exam. Small roundings of the score will be made to reflect the student's participation in the course: contributions to the debate of the topics, questions raised, and their resolution.

The final mark, M, will be

\[ M = \text{maximum} \{0.25 \ P + 0.75 \ E, \ E\} \]

where

- \( P \) = mark obtained in practice mini-projects (between 0 and 10)
- \( E \) = mark of the final exam (between 0 and 10)

A student will pass the course if \( P \geq 4 \) and \( M \geq 5 \).

If the group of students is not large, the final exam might be oral. In that case, the exam will consist of a first block of conceptual questions, and a second block of questions regarding the exercises solved in class.

**Regulations for carrying out activities**
To solve the final exam, the student will need a calculator able to perform matrix computations. A six-page summary of the course can also be brought.
Bibliography

Basic:


Complementary:


Others resources:

Hyperlink

http://www.iri.upc.edu/gfrd

Web page with the full contents of the course, including the lecture notes and slides used in class, the exercises and miniprojects, and exams from previous years.