Robotics 2

Introduction

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Robotics 2 – 2020/21

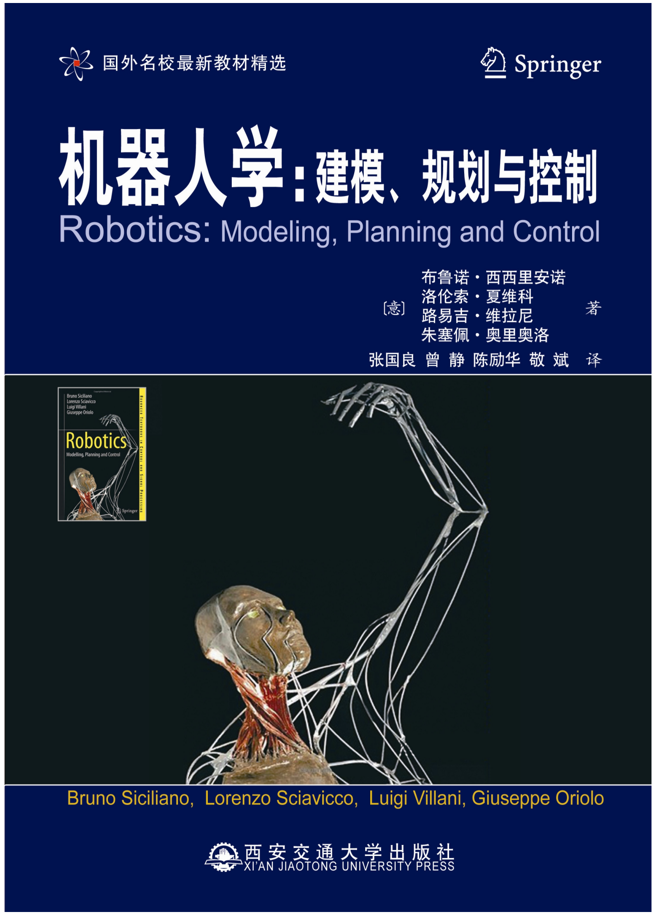
- II semester: Monday, February 22 – Wednesday, May 26, 2021
- masters: Artificial Intelligence and Robotics & Control Engineering
- credits: 6 = 150h (1 ECTS = 25h of student work)
  - ~50h of Video Lectures (VL) recorded last year: available on YouTube in **Robotics 2 playlist** of Video DIAG – Sapienza channel
  - ~30h of lectures in the classroom or on Zoom, with
    - Questions & Answers on material covered in the previous VL
    - Exercises (with blackboard) + Discussions + (Remote) Midterm Test
  - ~70h of individual study
- lecture schedule: Monday (8:00-10:00) OR Wednesday (14:00-17:00)
  - in classroom B2 or via Zoom (with Sapienza institutional email only) https://uniroma1.zoom.us/j/83717753465?pwd=QU8zS0xCWTcvb1Z3N0pxOW02RGxHdz09
  - ~once a week, variable schedule, depending on needs and progress…
- G-group: register to https://groups.google.com/a/diag.uniroma1.it/g/robotics2_2020-21

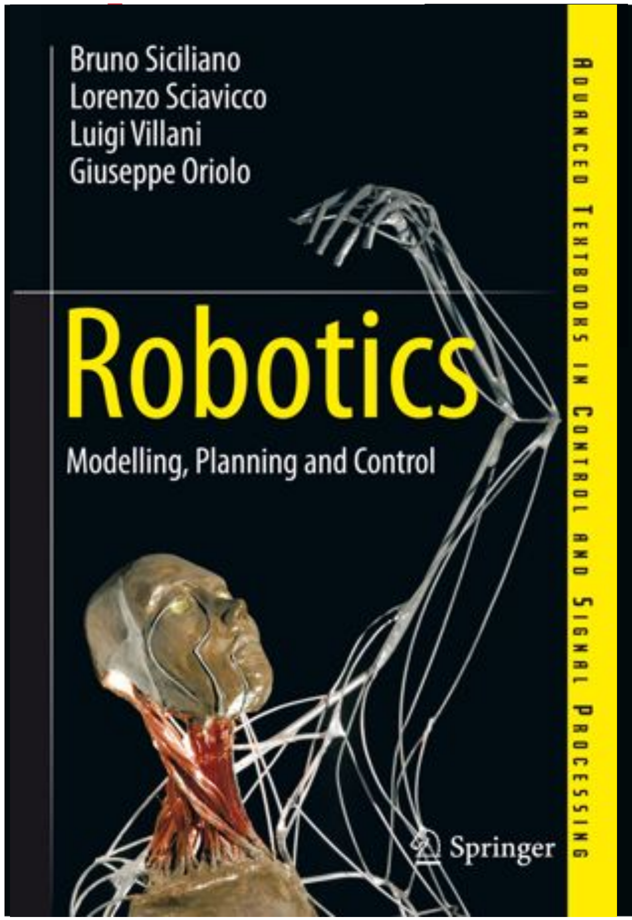
General information

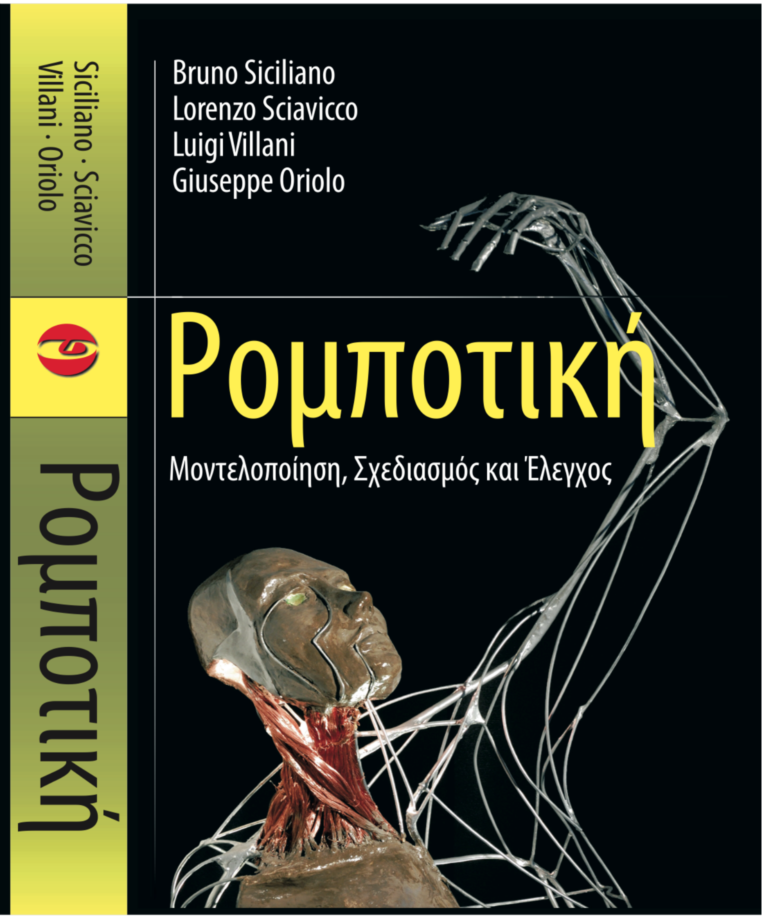
- prerequisites
  - Robotics 1 as prerequisite (see www.diag.uniroma1.it/deluca/rob1_en.php)
- aims
  - advanced kinematics & dynamic analysis of robot manipulators
  - design of sensory feedback control laws for free motion and interaction tasks
- textbook
  - B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo: *Robotics: Modelling, Planning and Control*, 3rd Edition, Springer, 2009
- related courses
  - Autonomous and Mobile Robotics: 1st semester of Y2, 6 credits
  - Elective in Robotics: whole Y2, 12 credits (four modules)
    or Control Problems in Robotics: 6 credits (two out of four modules)
  - Medical Robotics: 2nd semester of Y2, 6 credits

An international textbook...

B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo: *Robotics: Modelling, Planning and Control*, 3rd Edition, Springer, 2009







Robotics

- algorithms for robotics*
  - process **inputs from sensors** that provide noisy and partial data
  - build **geometric and physical models** of the robot and the world
  - **plan high- and low-level actions** at different time horizons
  - **execute these actions on actuators** with uncertainty/limited precision
- design & analysis of robot algorithms raise a unique combination of questions from many fields
  - **control theory**
  - computational geometry and topology
  - **geometrical and physical modeling**
  - reasoning under uncertainty
  - probabilistic algorithms and game theory
  - theoretical computer science

* = modified from intro to WAFR 2016

Program - 1

all on fixed-base robot manipulators!

- advanced kinematics
  - kinematic calibration
  - kinematic redundancy and related control methods
- dynamic modeling of manipulators
  - direct and inverse dynamics
  - Euler-Lagrange formulation
  - Newton-Euler formulation
  - properties of the dynamic model
  - identification of dynamic parameters
  - inclusion of flexibility at the joints
  - inclusion of geometric constraints

Q: why/when do we need dynamics for robot control?

Program - 2

- design of feedback control laws (torque input commands)
  - free motion tasks
    - set-point regulation
      - PD with gravity cancellation or compensation
      - PID or saturated PID
      - iterative learning for gravity compensation
    - trajectory tracking
      - feedback linearization and input-output decoupling (in different spaces)
      - passivity-based control
      - adaptive (and robust) control
      - on-line learning
  - interaction tasks with the environment
    - compliance/admittance control
    - impedance control
    - hybrid force/velocity control

Program - 3

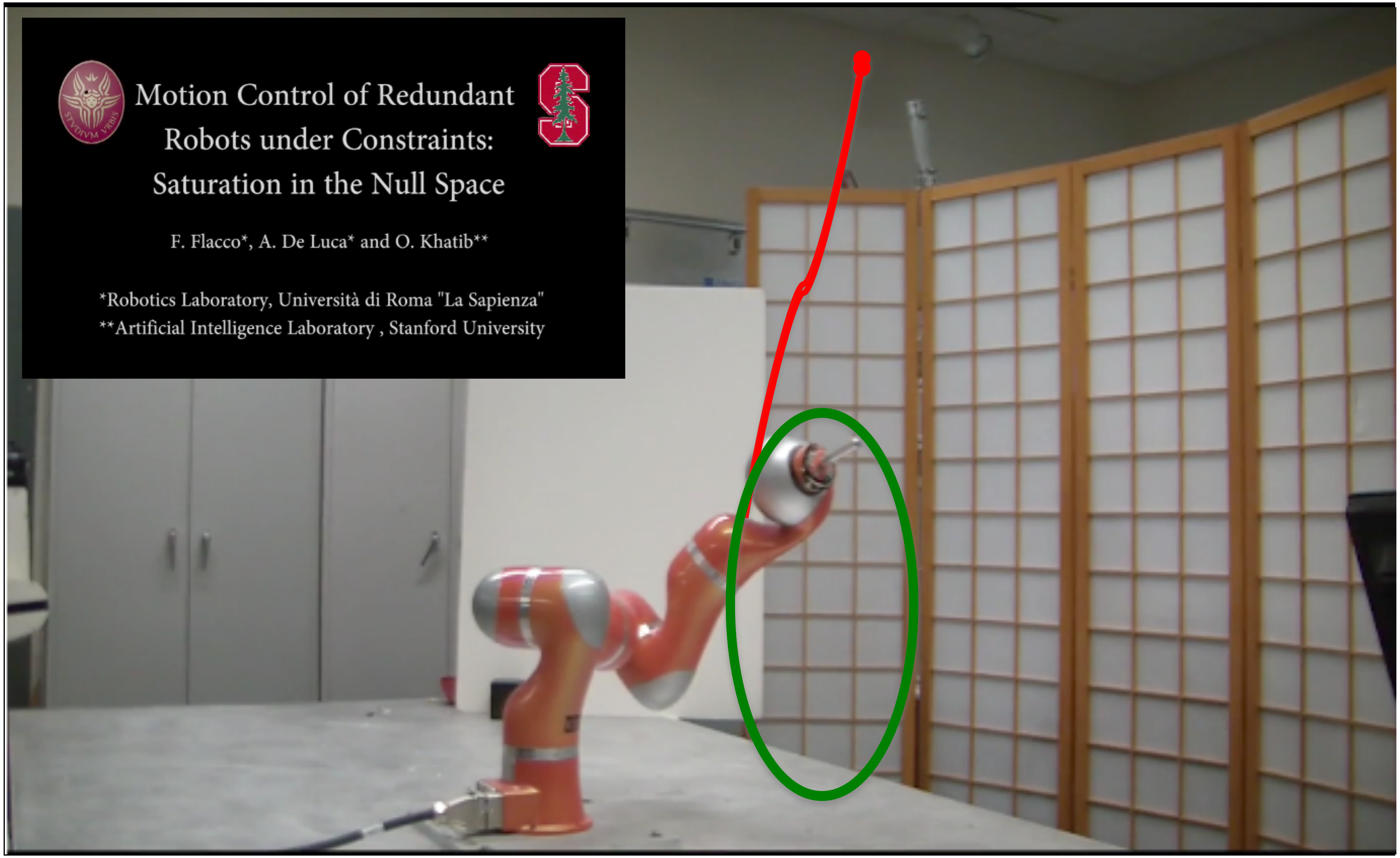
- exteroceptive feedback control laws
  - image- and position-based visual servoing
    - kinematic treatment
- research-oriented seminars
  - diagnosis of robot actuator faults
  - physical Human-Robot Interaction (pHRI)
    - safety: sensor-less collision detection and robot reaction
    - coexistence: collision avoidance while sharing workspace
    - collaboration: intentional exchange of contact forces
- simulation tools
  - Matlab/Simulink (including Robotics Toolbox of Peter Corke)
  - CoppeliaSim (formerly V-REP)

Sneak preview of videos follows ...

- kinematic redundancy and related control methods
- robot dynamic modeling and identification
- interaction with the environment: force and motion control
- motion control in the presence of joint flexibility or variable stiffness actuation
- safe physical human-robot interaction & collaboration

Kinematic/dynamic control and redundancy

SNS algorithm handles hard bounds on robot motion

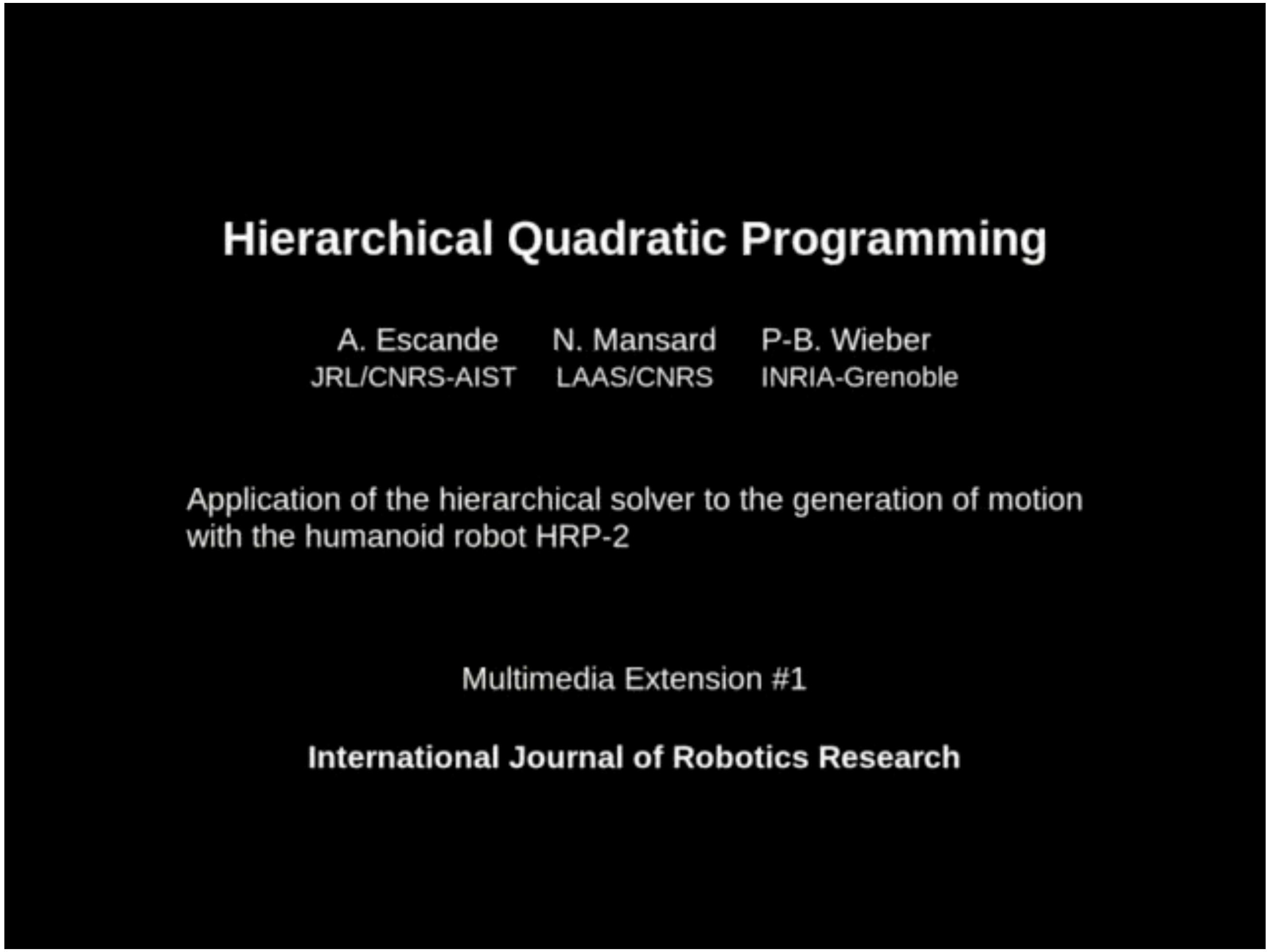


KUKA LWR4 robot

video DIAG Sapienza/Stanford, IEEE ICRA 2012

Kinematic control and redundancy

(standing) HRP-2 humanoid robot video @LAAS/CNRS Toulouse



HQP approach for multiple equality and inequality tasks with priorities

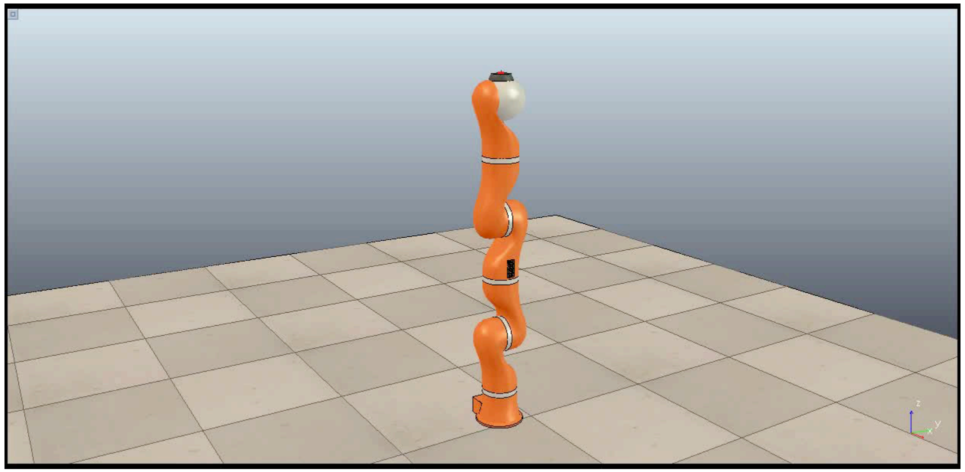
Dynamic modeling and identification

data acquisition
for identification

2 videos ICRA 2014 @DIAG Robotics Lab

model validation
by torque prediction

KUKA LWR4+ robot
with joint torque
sensing



dynamic
simulation
with V-REP

video

Dynamic modeling and identification

e.g., linear parametrization of gravity term in robot dynamic model

$$\boldsymbol{\pi}_g = \begin{pmatrix} c_{7y}m_7 \\ c_{7x}m_7 \\ c_{6x}m_6 \\ c_{6z}m_6 + c_{7z}m_7 \\ c_{5z}m_5 - c_{6y}m_6 \\ c_{5x}m_5 \\ c_{5y}m_5 + c_{4z}m_4 + d_2(m_5+m_6+m_7) \\ c_{4x}m_4 \\ c_{4y}m_4 + c_{3z}m_3 \\ c_{2x}m_2 \\ c_{3x}m_3 \\ c_{2z}m_2 - c_{3y}m_3 + d_1(m_3+m_4+m_5+m_6+m_7) \end{pmatrix}$$

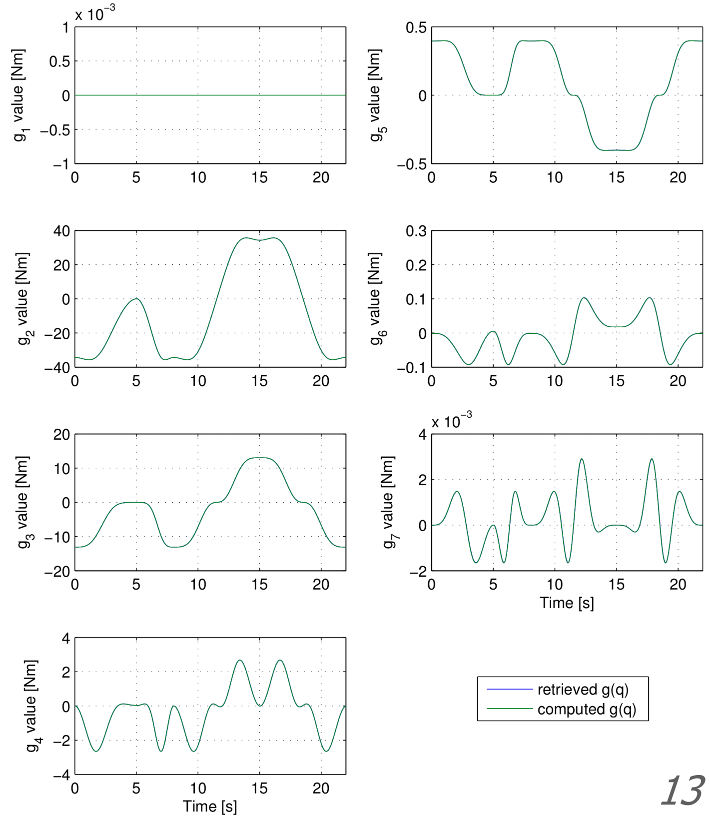
$$\boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{Y}_g(\boldsymbol{q})\boldsymbol{\pi}_g$$

symbolic expressions of gravity-related dynamic coefficients

$$\hat{\boldsymbol{\pi}}_g = \begin{pmatrix} 9.5457 \times 10^{-4} \\ -2.9826 \times 10^{-4} \\ 8.3524 \times 10^{-4} \\ 0.0286 \\ -0.0407 \\ -6.5637 \times 10^{-4} \\ 1.334 \\ -0.0035 \\ -4.7258 \times 10^{-4} \\ 0.0014 \\ 9.4532 \times 10^{-4} \\ 3.4568 \end{pmatrix}$$

numerical values identified through experiments

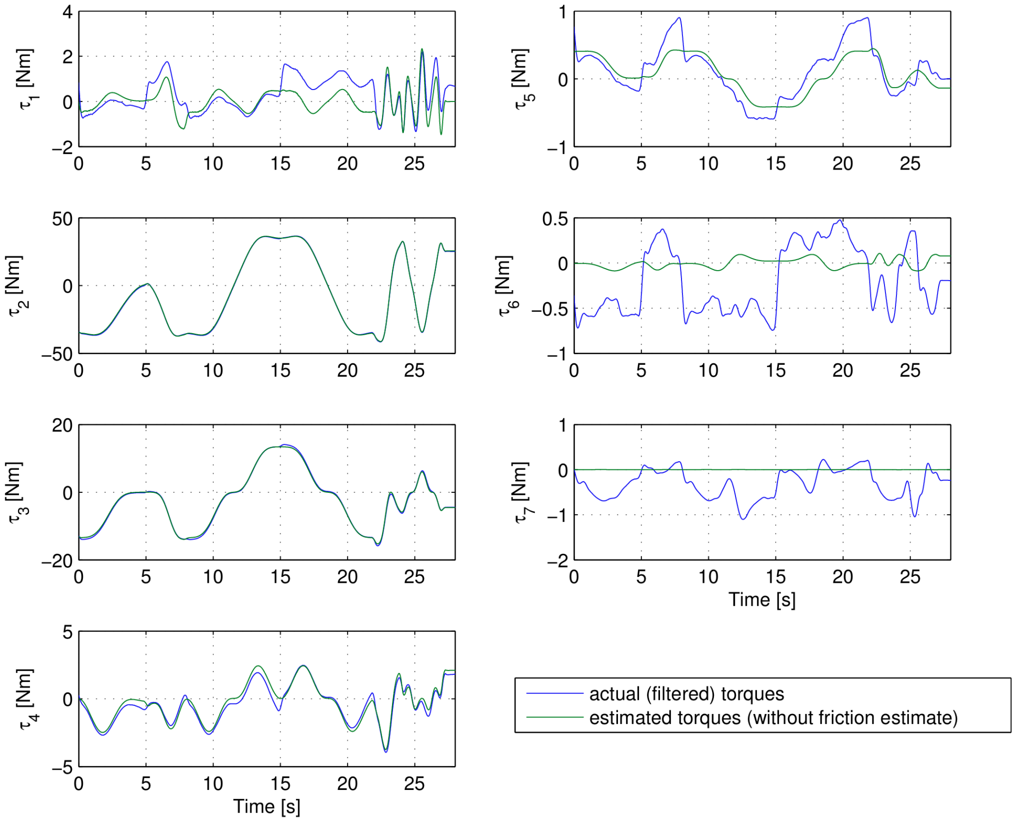
gravity joint torques prediction/evaluation on new validation trajectory

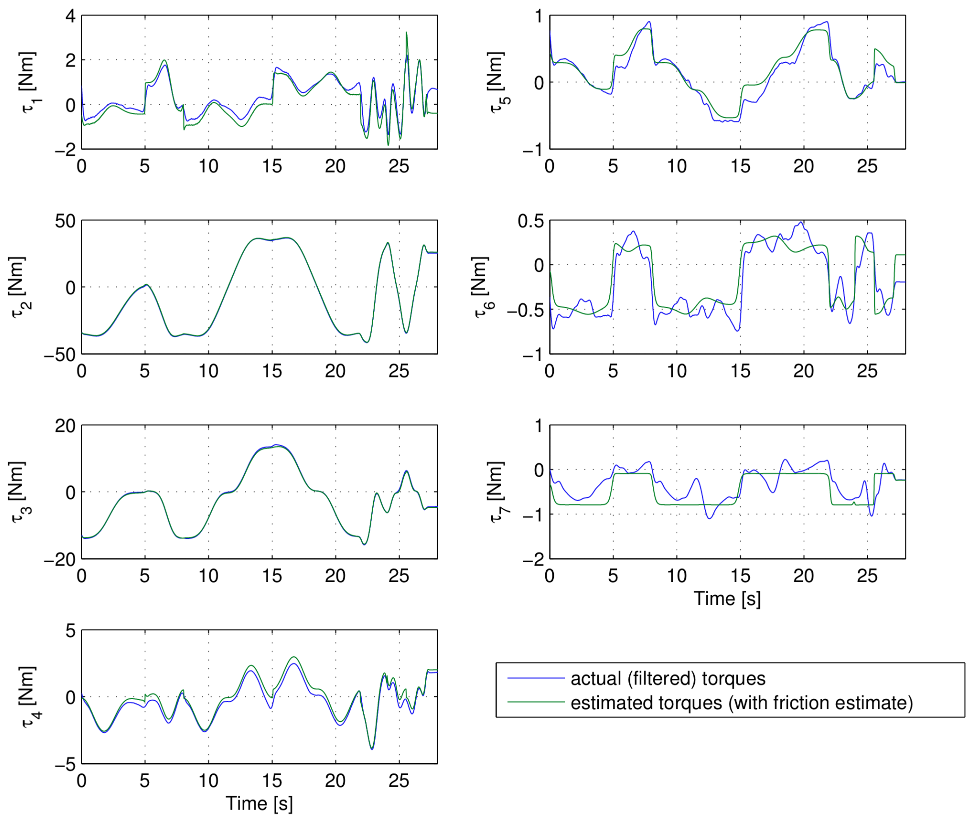


Dynamic modeling and identification

complete dynamic model estimation vs. joint torque sensor measurement

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{c}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} - \boldsymbol{\tau}_{friction} \qquad \boldsymbol{\tau}_{meas}$$



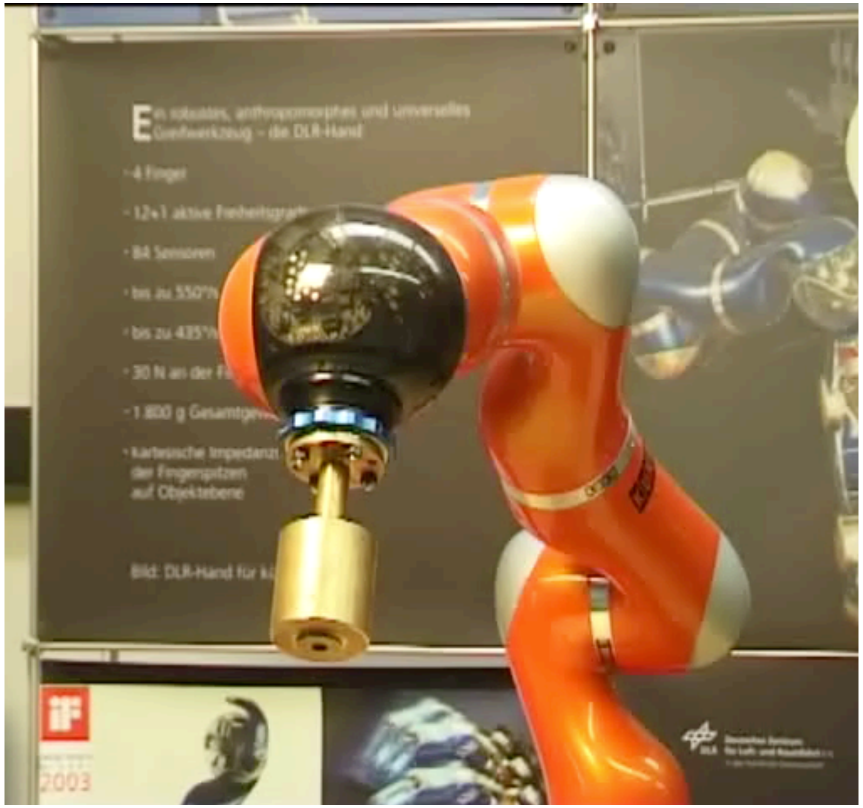


without the use of a joint friction model

including an identified joint friction model

Motion and interaction control

2 videos @DLR München

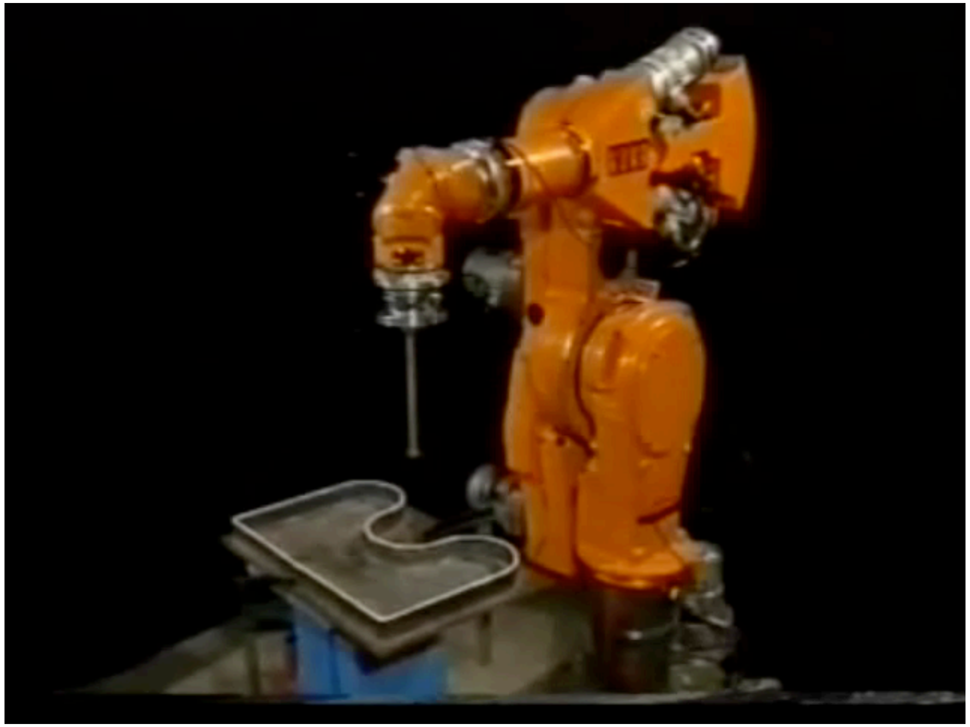


low-damped oscillations due to flexibility
of robot transmissions at the joints
(use of Harmonic Drives)

end-effector response to forces
with impedance control
(selective behavior in different directions)

Control of environment interaction

2 video clips extracted from Springer Handbook of Robotics - Multimedia

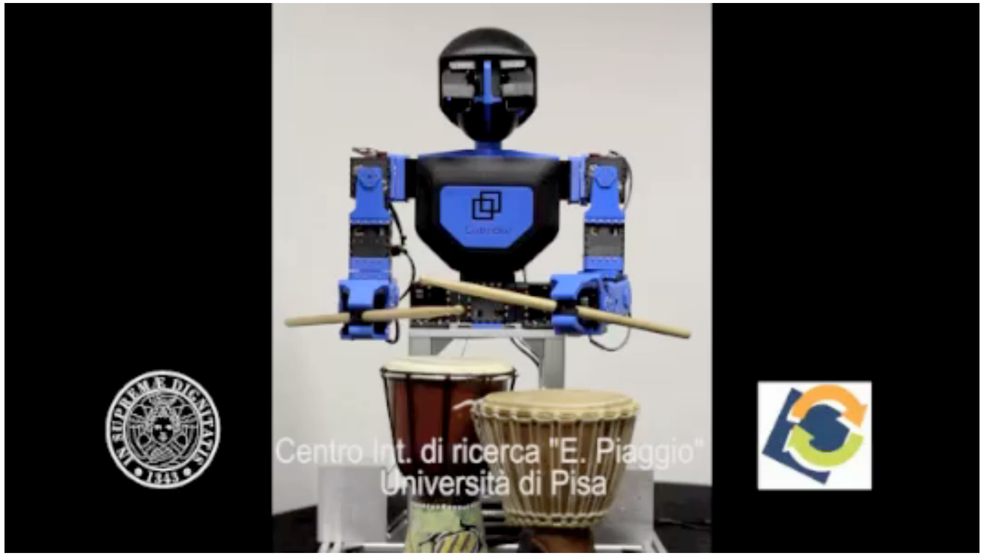


surface contour following

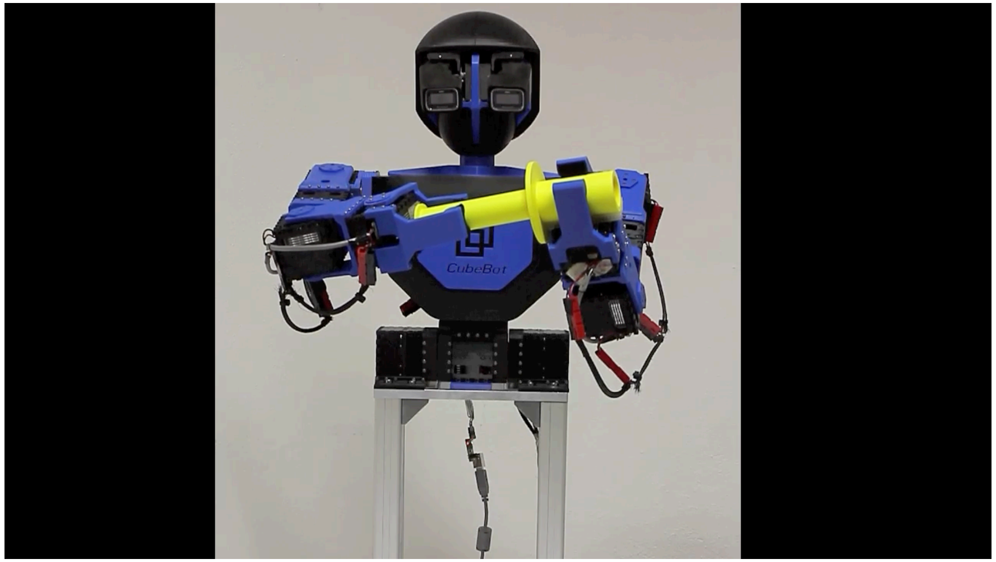
peg-in-hole insertion strategy

De Schutter *et al* @KU Leuven, Belgium (mid '90s)

Motion control with VSA



3 videos
@University of Pisa



modular, low-cost
qbmove units

compliant motion with Variable Stiffness Actuators

Sensorless collision detection

2 videos @DLR München

during my sabbatical in 2005-06

residual method to detect collisions: uses robot dynamic model, encoder readings, commanded torques (in case of rigid joints)

master student Sami Haddadin in 2006

NEVER DO THIS!

(unless you're 100% sure of your research results …)

Safe human-robot collaboration

finalist video IROS 2013 @DIAG Robotics Lab

Physical human-robot interaction control

video ICRA 2015 @DIAG Robotics Lab

Contacts

- student hours: Tuesdays 12:00-13:30 (until June 2021)
  - via G-Meet: https://meet.google.com/chp-fghs-fri
  - … maybe later on: c/o A-210, left wing, floor 2, DIAG
  - other dates: send an email, check also "My travel dates" on web site
- communications:
  - use the G-group for questions and doubts: everyone would benefit!
  - by mail (personal issues): deluca@diag.uniroma1.it
- URL: http://www.diag.uniroma1.it/deluca
- course materials:
  - http://www.diag.uniroma1.it/deluca/rob2_en.html
  - slides in pdf, link to video lectures, all shown video clips (zipped), syllabus, written exams (most with solutions), …
- video channel: http://www.youtube.com/user/RoboticsLabSapienza

Exams and Master Theses

- type of exam:
  - Remote Midterm Test (RMT) qualifies for final project
  - written test + oral part (OR final project + oral presentation)
- schedule for academic year 2020/21:
  - 2 sessions at the end of this semester
    - June 11, 9:00, room B2 and July 12, 9:00, room B2
  - 1 session after the summer break
    - September 10, 9:00, room B2
  - 2 sessions at the end of the first semester of next year
    - January and February 2022, dates/rooms tbd
  - booking ready in infostud (code 1021883), up to 10 days before, only one session is open at a time
  - *2 extra sessions* ***only*** *for students of previous years, part-time, etc.*
    - in April and October 2021
- theses: samples at DIAG Robotics Lab http://www.diag.uniroma1.it/labrob