Robotics 2

Introduction

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Robotics 2 – 2024-25

- II semester February 26 – May 28, 2025
- schedule Monday (8:00-10:00) - Wednesday (14:00-17:00), room B2
- master courses Artificial Intelligence and Robotics & Control Engineering
- credits 6 = 150h (1 ECTS = 25h of student work)
  - regular lectures in the classroom (~60h)
  - individual study and exercises (~90h)
  - if needed, see the video lectures (recorded in 2019-20) on YouTube in the Robotics 2 playlist of the Video DIAG – Sapienza channel
- G-group https://groups.google.com/a/diag.uniroma1.it/g/robotics2_2024-25

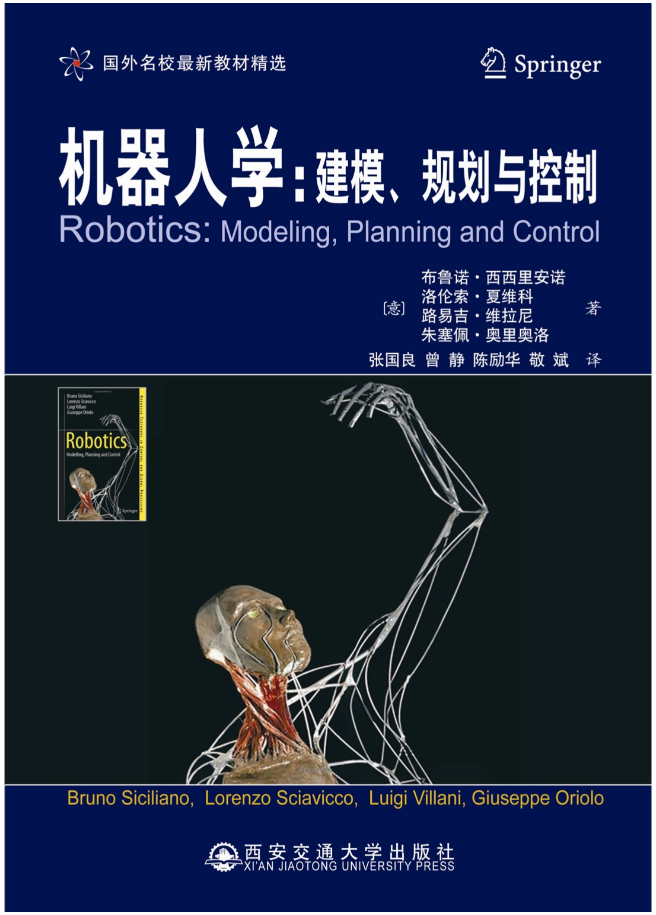
active links below these!

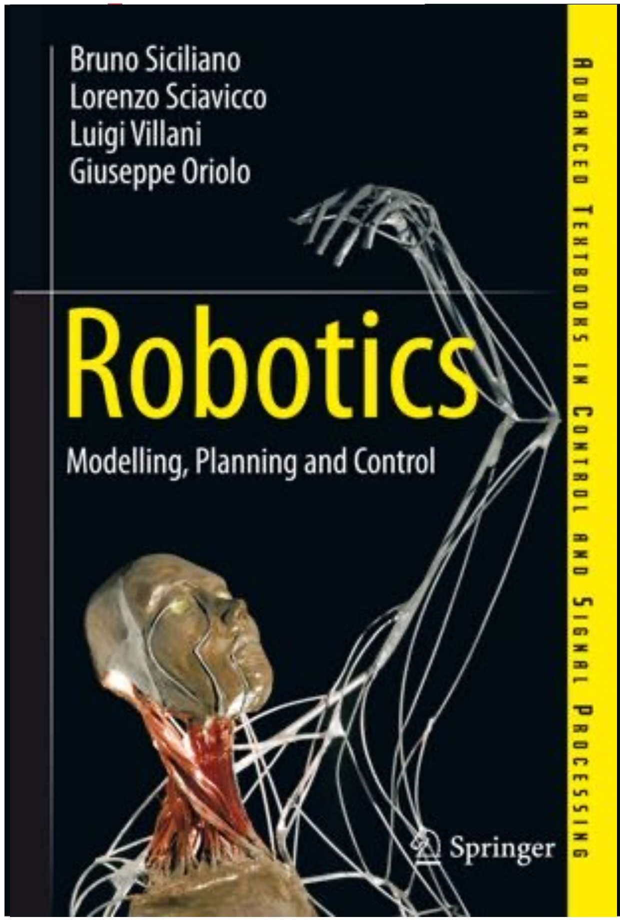
General information

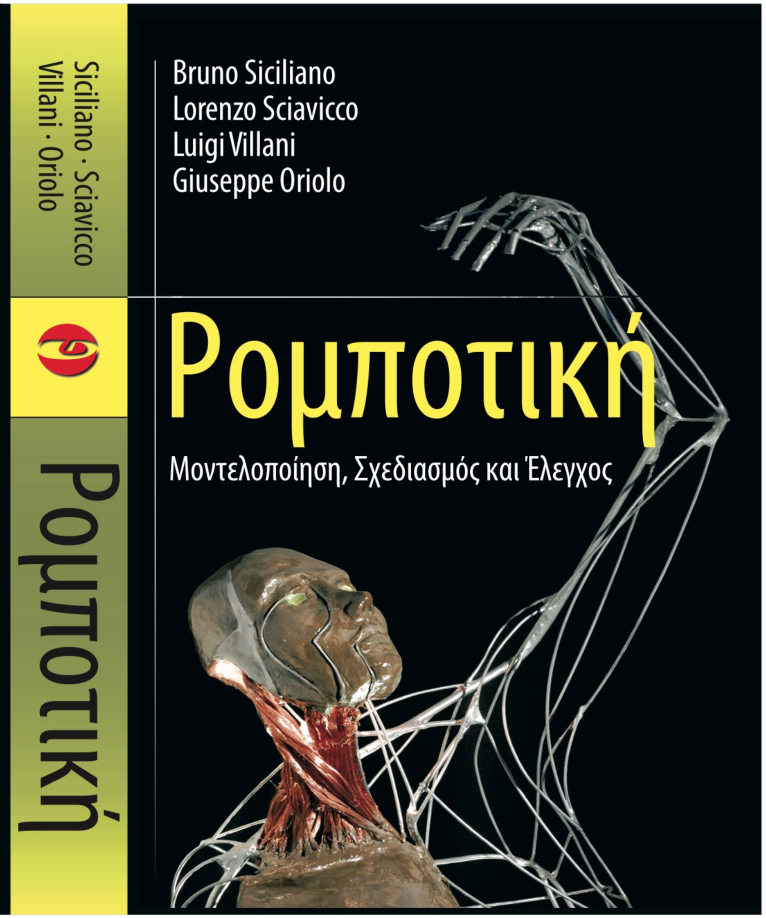
- prerequisites
  - Robotics 1 as a prerequisite (**mandatory** for the exam)
- aims
  - advanced kinematics & dynamic analysis of robot manipulators
  - design of feedback control laws for free motion and interaction tasks
- related courses
  - Autonomous and Mobile Robotics 1st semester of year 2, 6 credits
  - Elective in Robotics whole year 2, 12 credits (four modules)
    or Control Problems in Robotics 6 credits (two out of four modules)
  - Probabilistic Robotics 1st semester of year 2, 6 credits
  - Medical Robotics 2nd semester of year 2, 6 credits
- research video channel www.youtube.com/user/RoboticsLabSapienza

An international textbook

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

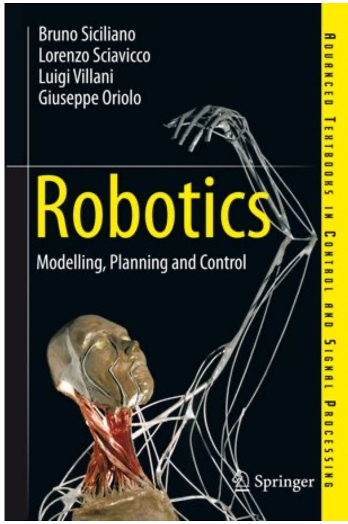


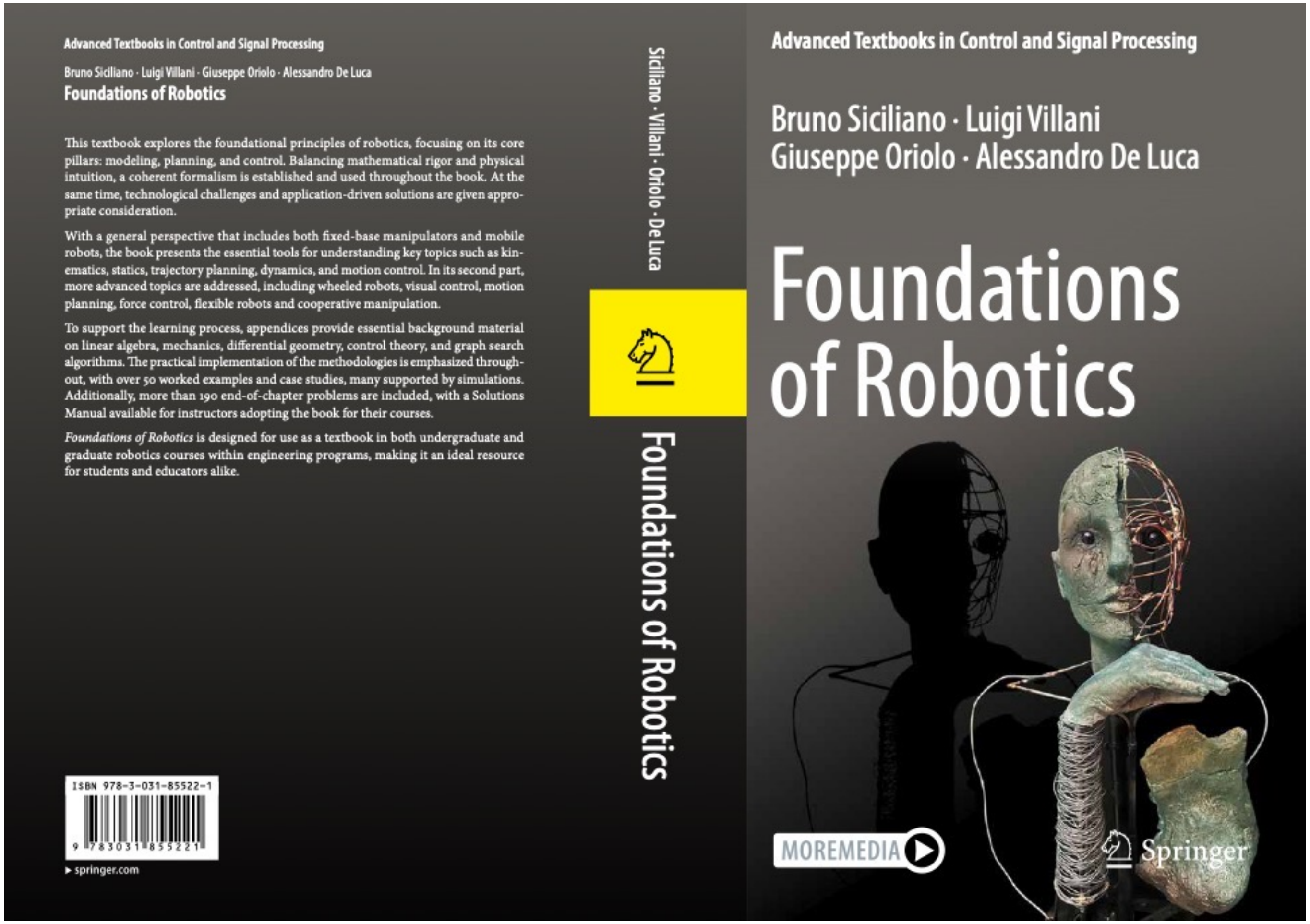




… fully revised textbook coming!

B. Siciliano, L. Villani, G. Oriolo, A. De Luca: **Foundations of Robotics** appears in April 2025 ⇒ Springer link





700+ pages covering

- Robotics 1
- Robotics 2
- Autonomous and Mobile Robotics

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
  - **geometric and physical modeling**
  - reasoning under uncertainty
  - probabilistic algorithms and game theory
  - theoretical computer science

* = modified from intro to WAFR 2016

all on fixed-base robot manipulators!

Program - 1

- 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: are redundant robots "special" manipulators?

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

Task-related redundancy

video of ABB robot in laser cutting

6-DOF robot for a 5-dimensional task
= 1 degree of kinematic redundancy

Robot dynamics and control

video of WAM by Barrett Technology

@Ishikawa Lab, Tokyo University, 2012

Robot dynamics and control

video of Atlas by Boston Dynamics, 2017

https://youtu.be/fRj34o4hN4I

Program - 2

- design of feedback control laws
  - free motion tasks
    - set-point regulation
      - PD with gravity cancellation or compensation
      - PID or saturated PID
      - iterative learning for gravity compensation
      - regulation in the Cartesian/task space
    - trajectory tracking
      - feedback linearization and input-output decoupling
        - in the joint space
        - in the Cartesian/task space
      - passivity-based control
      - adaptive (and robust) control
      - on-line learning

e.g., on a soft robot

e.g., on a 7R robot

Q: why/when is kinematic control not sufficient?

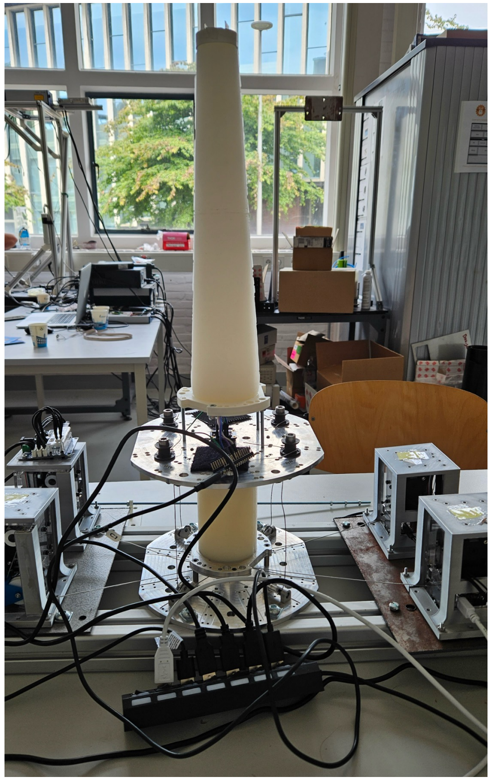
torque input commands

Iterative learning under gravity

continuum soft robots

- hard to model: ∞-dimensional $\Longrightarrow$ PCC (= Piecewise Constant Curvature)
- difficult estimation of the dynamic parameters

video



two-segment prototype @TU Delft

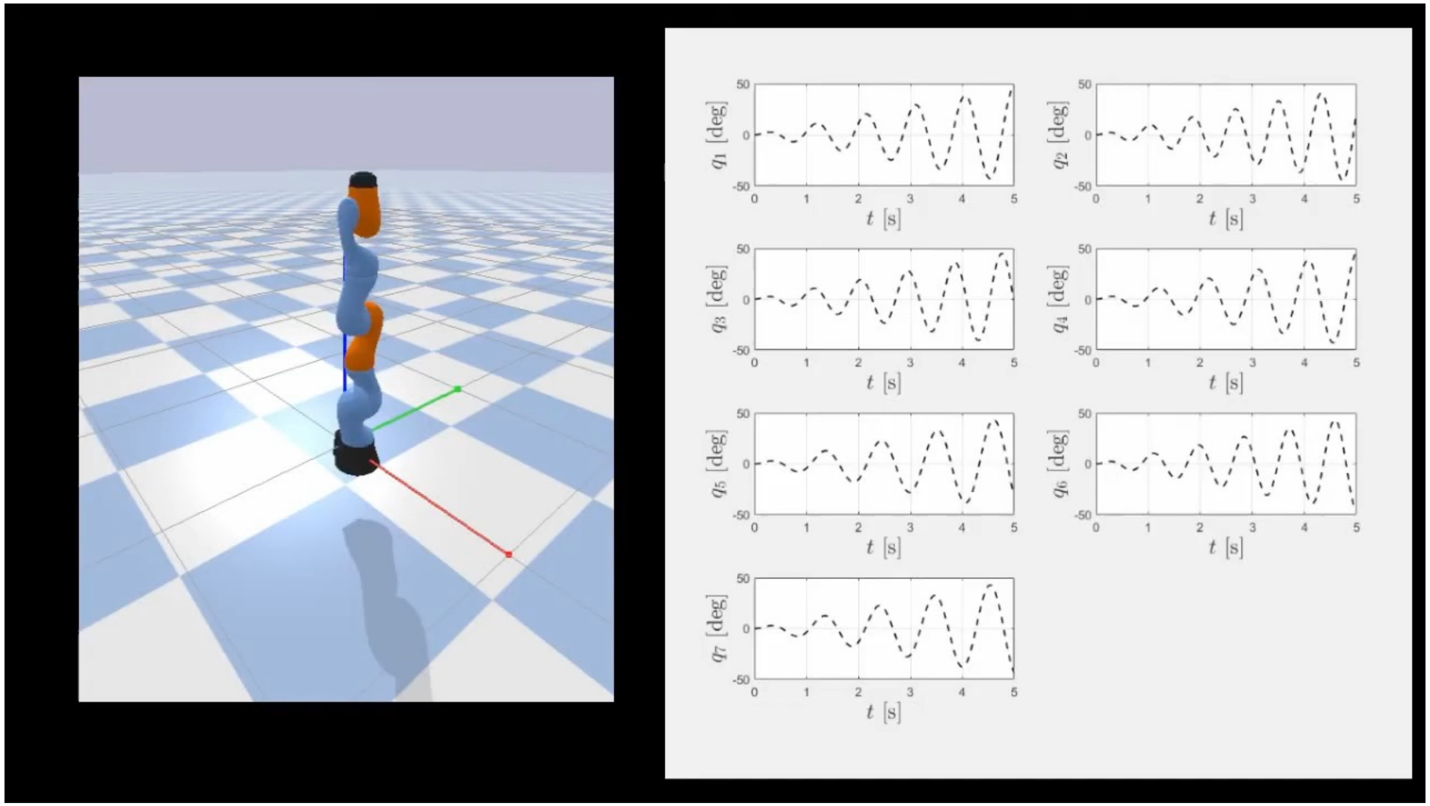
I-RIM 2022 conference

Feedback linearization and inverse dynamics

rigid multi-link robots

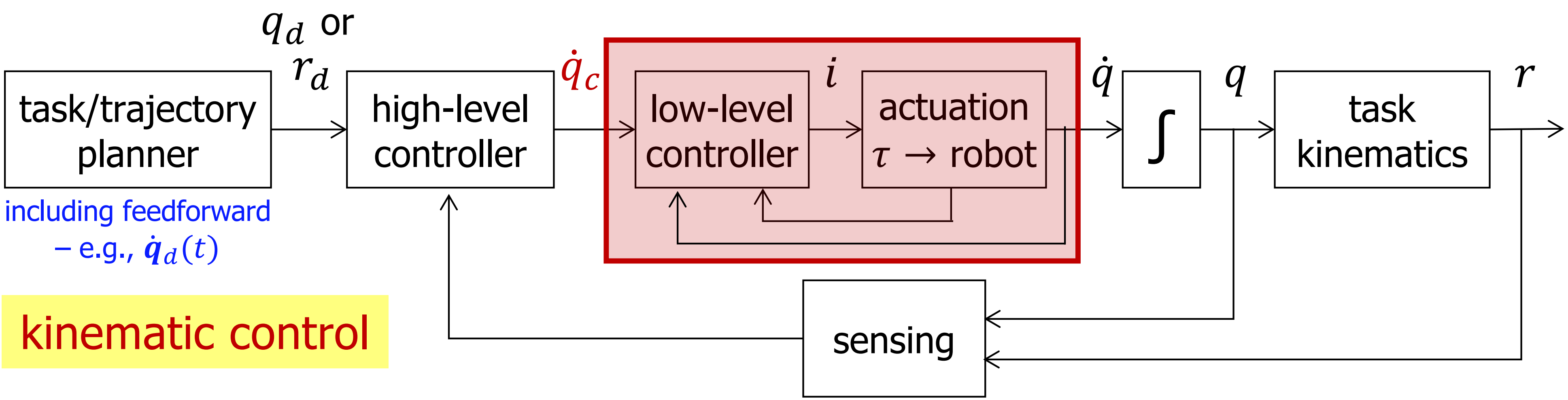
- use a complete dynamic model, with feedback reaction to tracking errors
- uncertainties handled by off-line identification, on-line adaptation, …

video



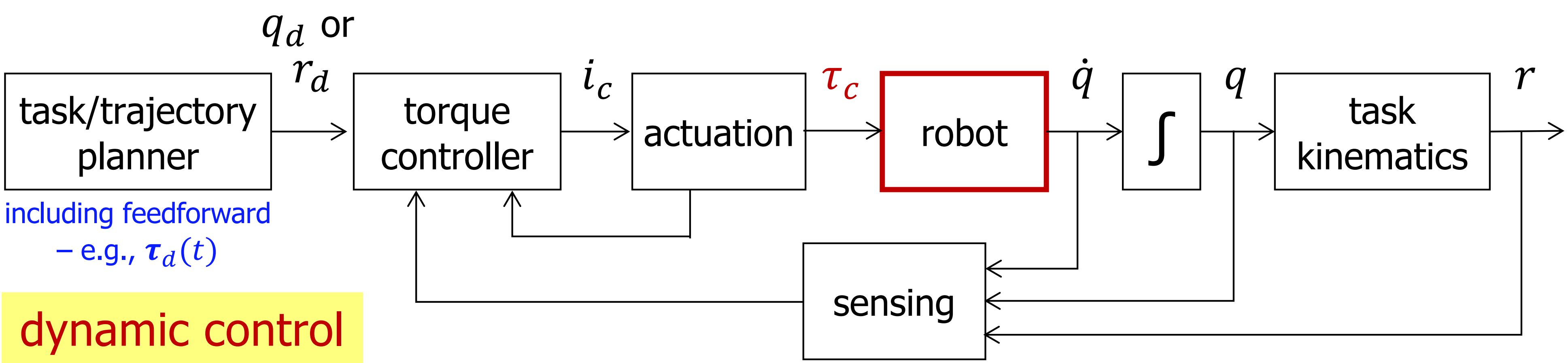
7R KUKA LWR4+ robot DEI UniPadova, I-RIM 2020 conference

Position- vs. torque-controlled robots



kinematic control

… acceleration $\ddot{q}$, mass, gravity, inertia, centrifugal forces, friction?



dynamic control

- both modes may be present even in the same robotic system

Program - 3

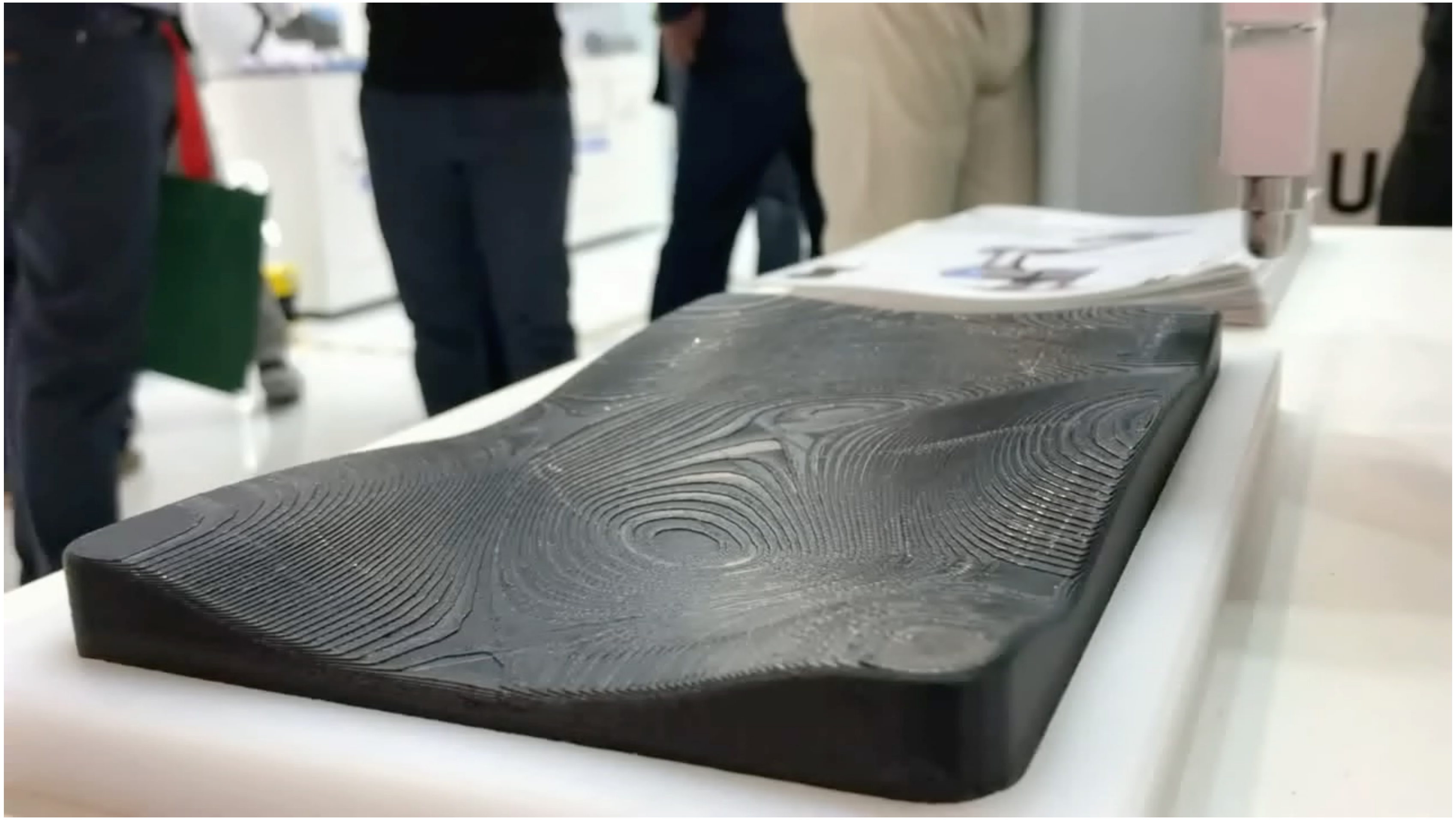
- design of feedback control laws
  - interaction tasks with the environment
    - compliance/admittance control
    - impedance control
    - hybrid force/velocity control
  - image- and position-based visual servoing
    - kinematic control treatment only
- fault diagnosis
  - detection and isolation of robot actuator faults
  - extension to a class of sensor faults
- simulation tools
  - Matlab/Simulink (including Robotics Toolbox)
  - CoppeliaSim (formerly V-REP)

in general, torque input commands

Q: why multiple control laws for handling the interaction?

Interacting with a rigid, irregular surface

video

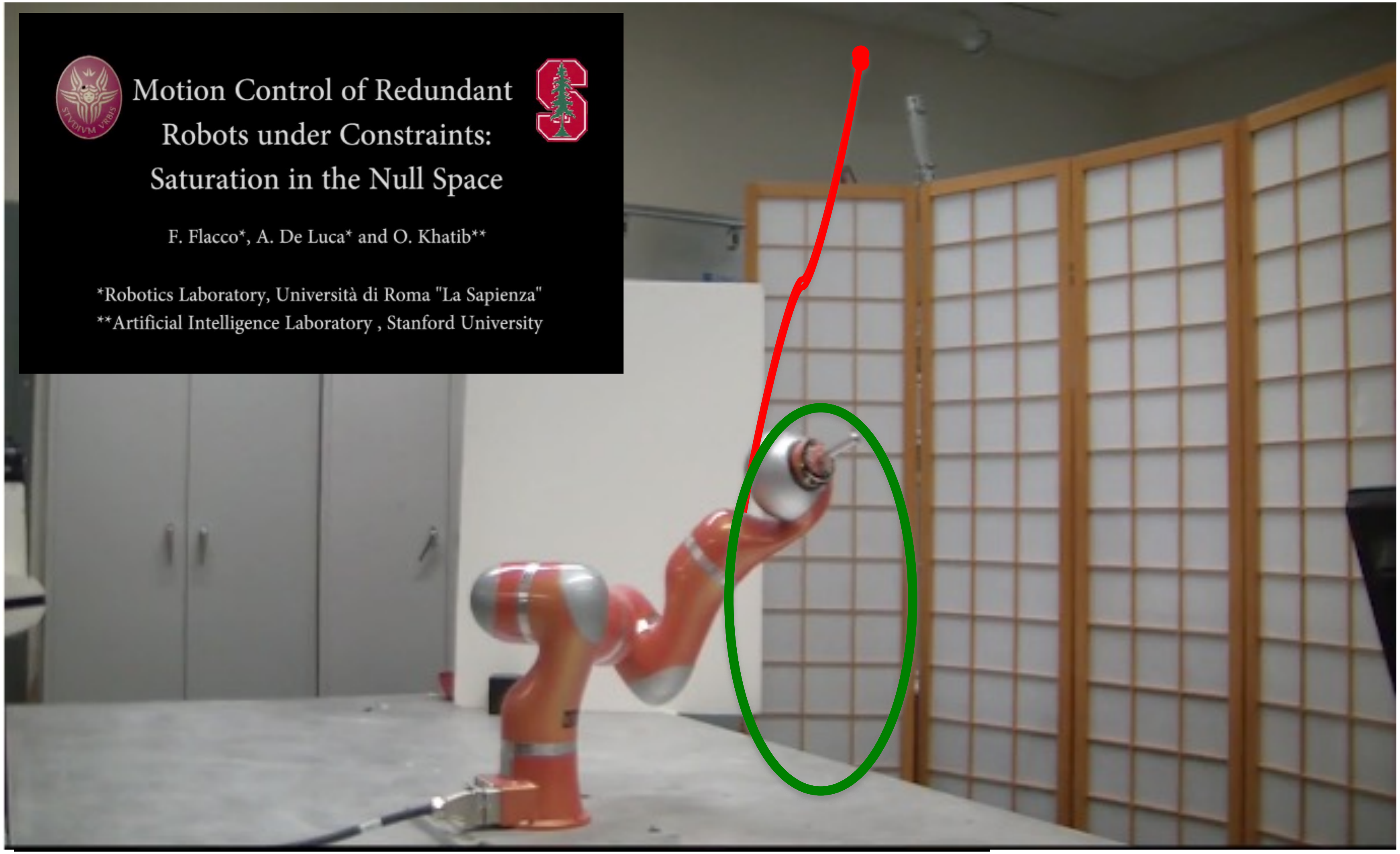


more appropriate control law? what is the goal?

Sneak preview of videos follows ...

- kinematic redundancy and related control methods
- robot dynamic modeling and identification
- motion control in the presence of joint flexibility
- interaction with the environment: force and motion control

Kinematic/dynamic control and redundancy
SNS algorithm handles hard bounds on robot motion

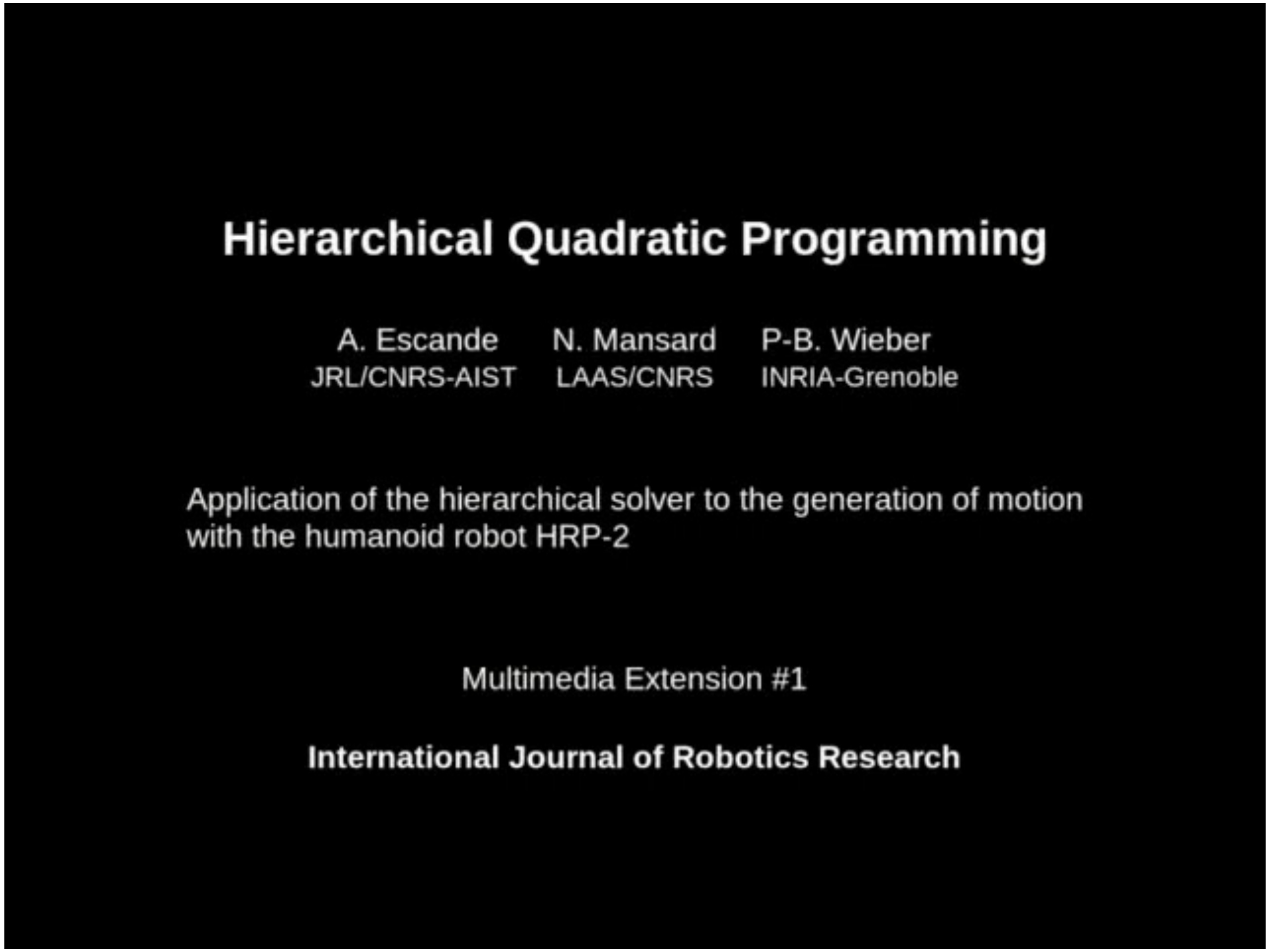


KUKA LWR4+ robot video DIAG Sapienza/Stanford, IEEE ICRA 2012

Kinematic control and redundancy

(standing) HRP-2 humanoid robot

video @LAAS/CNRS Toulouse



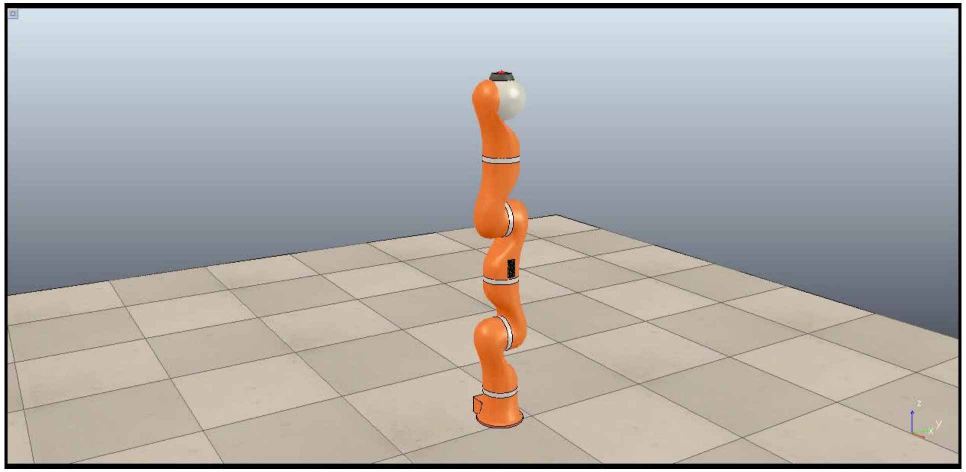
HQP approach for multiple equality and inequality tasks with priorities

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
CoppeliaSim
(was V-REP)

video

Dynamic modeling and identification

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

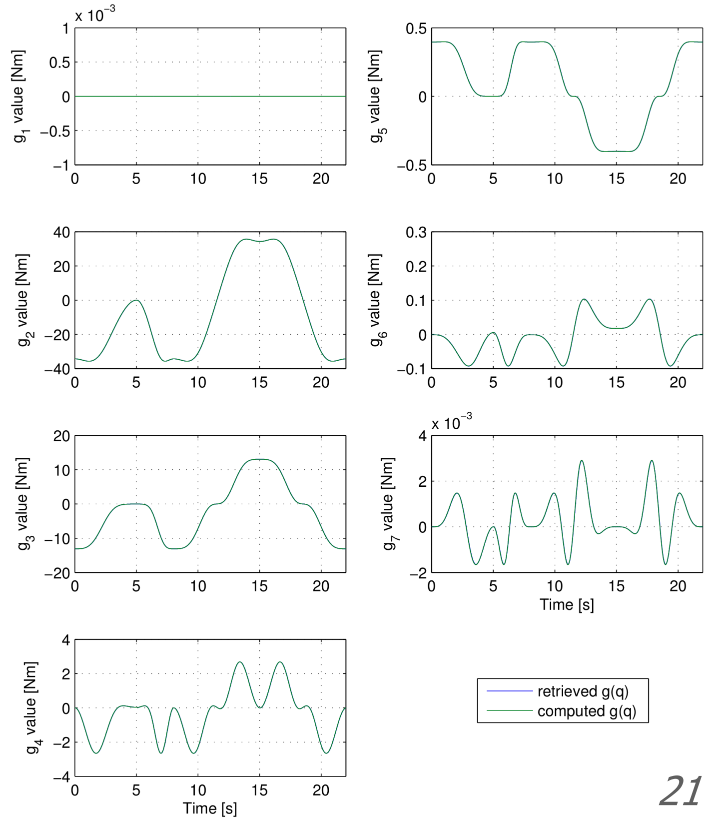
$$n = 7 \left\{ \boxed{\boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{Y}_g(\boldsymbol{q})\boldsymbol{\pi}_g} \right\} p_g = 12$$

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

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

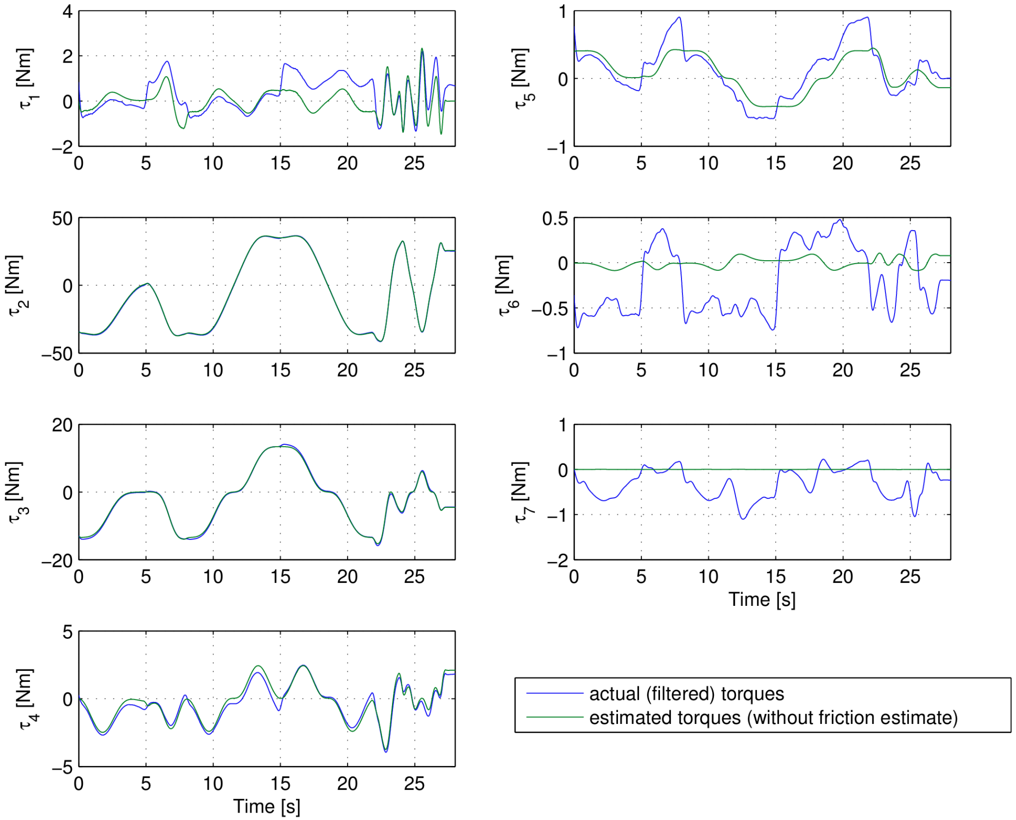


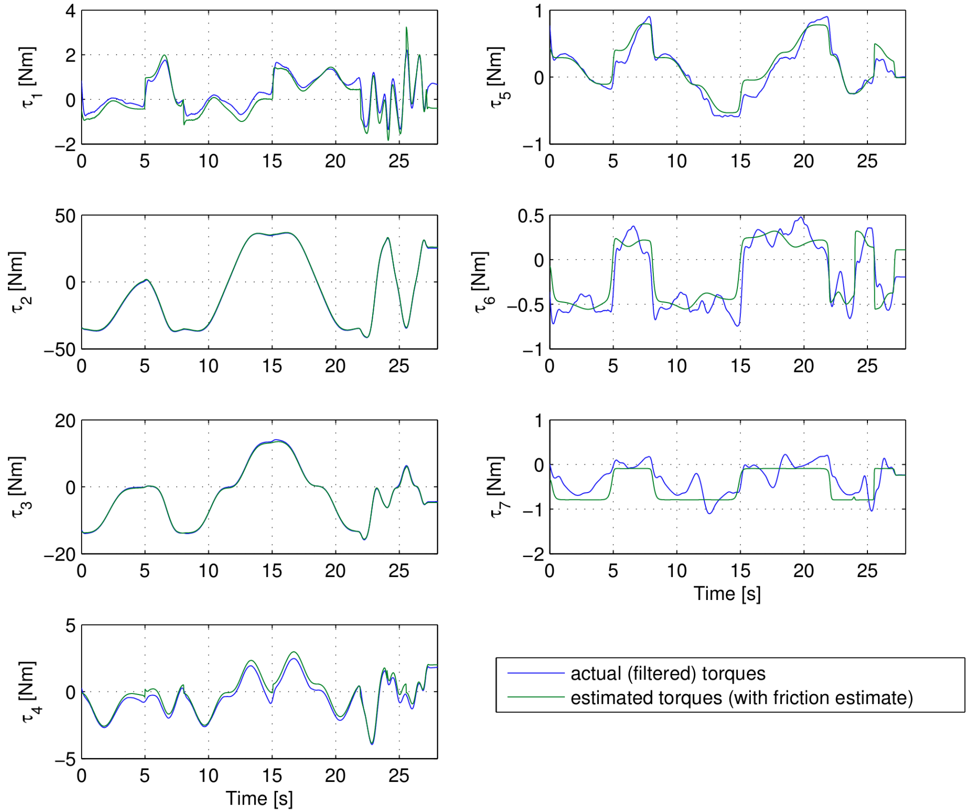
gravity joint torques prediction/evaluation on new validation trajectory

Dynamic modeling and identification

complete dynamic model estimation vs. joint torque sensor measurement

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





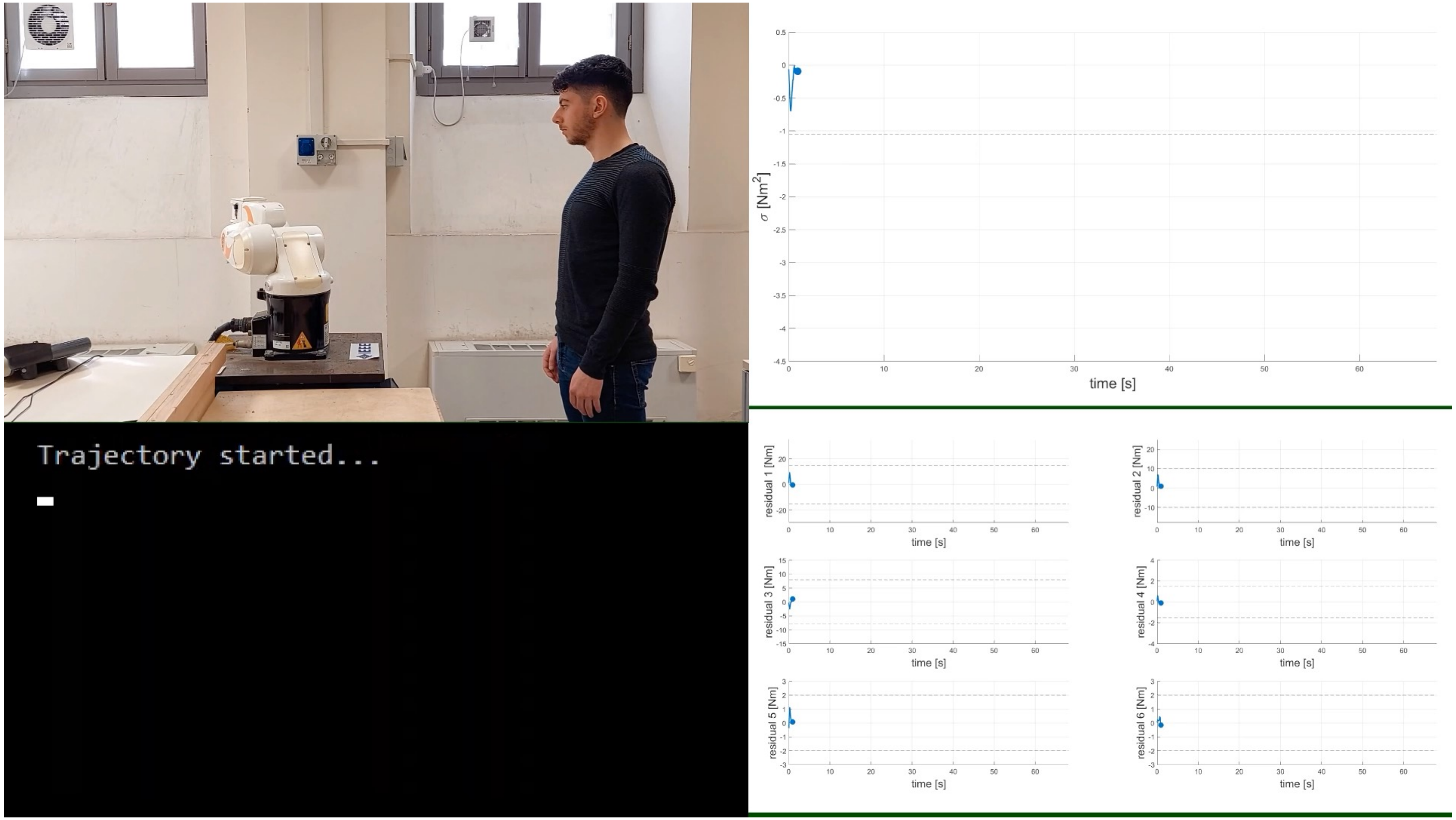
without the use of a joint friction model — including an identified joint friction model

Sensorless collision detection and isolation

using momentum observer (model-based)

video @DIAG Robotics Lab

KUKA KR5 Sixx R650 robot



I-RIM 2021 conference

Motion and interaction control

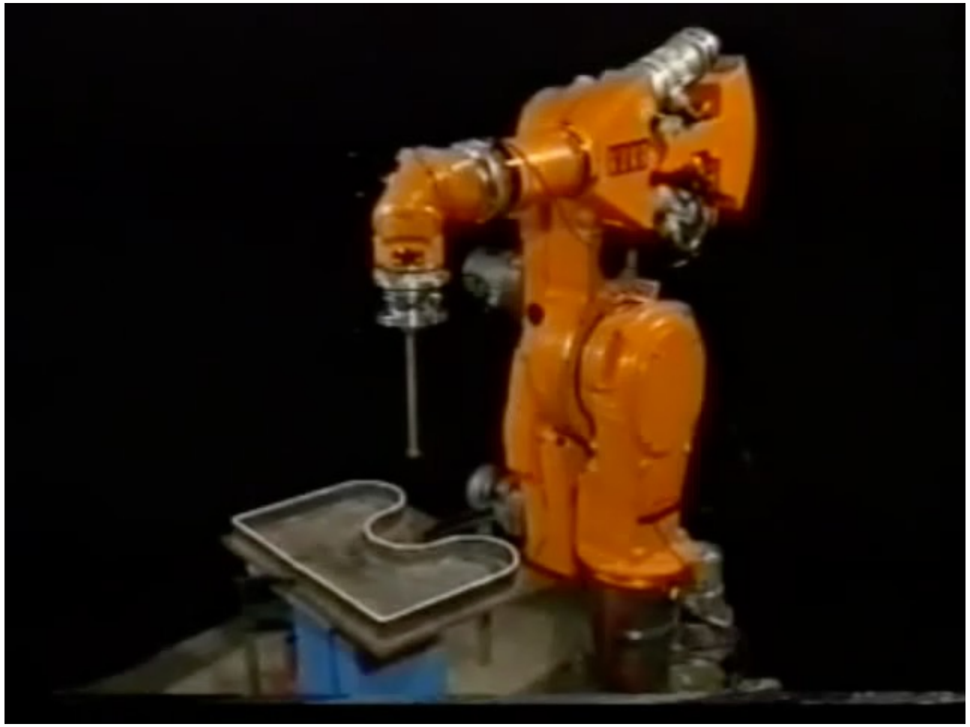
2 videos @DLR München

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)

Physical human-robot interaction control

video ICRA 2015 @DIAG Robotics Lab

Contacts

- student hours Tuesdays 12:00-13:30 (until early June 2025)
  - in presence A-210, left wing, floor 2, DIAG
  - via Zoom or G-Meet (see www.diag.uniroma1.it/deluca/Teaching.php)
  - send an email for other dates (check also My travel dates)
- communication mode
  - **use** the G-group for questions and doubts: everyone would benefit!
  - by mail (personal issues) deluca@diag.uniroma1.it
- URL www.diag.uniroma1.it/deluca
- course material
  - www.diag.uniroma1.it/deluca/rob2_en.php
  - pdf of slides, link to video lectures, videos shown in class (zipped), syllabus, written exams (most with solutions), …

Exams and Master Theses

- type of exam
  - midterm test qualifies for a final project (OR as part of the final exam)
  - final written exam OR final project + report + oral presentation
- exam schedule for academic year 2024-25
  - 2 sessions at the end of this semester
    - between June 3 and July 25
  - 1 session after the summer break
    - between September 1 and 23

  } to be published by April on infostud & course web page

  - 2 sessions at the end of the first semester of next year
    - January and February 2026
  - sign in on infostud (code 1021883) up to one week before, only one session is open at a time (OPIS questionnaire needed – filled in class!)
  - *2 extra sessions only for students of previous years, part-time, etc.*
    - periods: March 17 to April 18 and October 8 to November 6, 2025
- theses samples at DIAG Robotics Lab www.diag.uniroma1.it/labrob