



Robotics 2

Introduction

Prof. Alessandro De Luca

DIPARTIMENTO DI INGEGNERIA INFORMATICA
AUTOMATICA E GESTIONALE ANTONIO RUBERTI





Robotics 2 – 2019/20

- **second semester**
 - Monday, February 24 – Wednesday, May 27, 2020
- **courses of study**
 - Master in Artificial Intelligence and Robotics
 - Master in Control Engineering
- **credits: 6**
 - ~60 h of lectures, 90 h of individual study (1 ECTS = 25 h work)
- **classes**
 - Monday 08:00-10:00 (room **B2**, Via Ariosto 25)
 - Wednesday 14:00-17:00 (room **B2**, Via Ariosto 25)
- **video recordings of the course**
 - each lecture will be available soon after in the **Robotics 2 playlist** on the [Video DIAG – Sapienza](#) YouTube channel



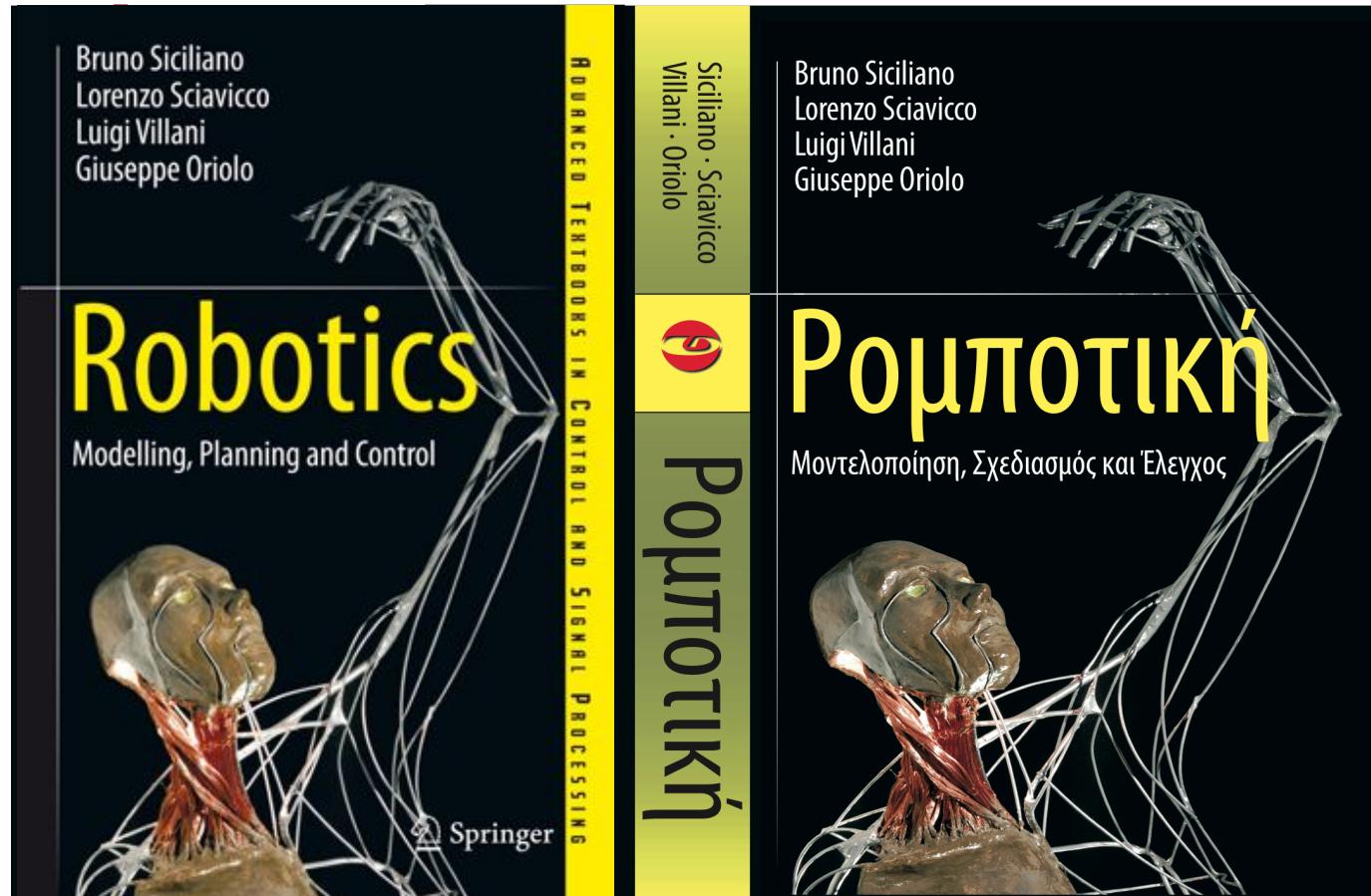
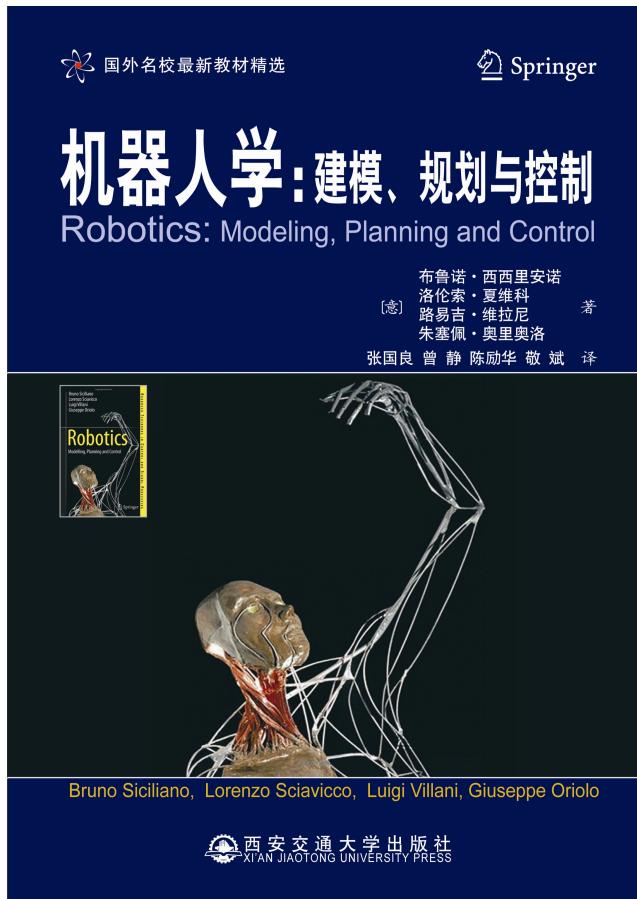
General information

- **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: first semester, 6 credits
 - Elective in Robotics: whole year, 12 credits (four modules)
or Control Problems in Robotics: 6 credits (two out of four modules)
 - Medical Robotics: second semester, 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

* = from intro to WAFR 2016



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

all on fixed-base
robot manipulators!



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
 - trajectory tracking
 - feedback linearization and input-output decoupling
 - passivity-based control
 - adaptive (and robust) control
 - interaction tasks with the environment
 - compliance 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**: sensorless collision detection and robot reaction
 - **coexistence**: collision avoidance while sharing workspace
 - **collaboration**: intentional exchange of contact forces
- **simulation tools**
 - Matlab/Simulink
 - CoppeliaSim (was V-REP)



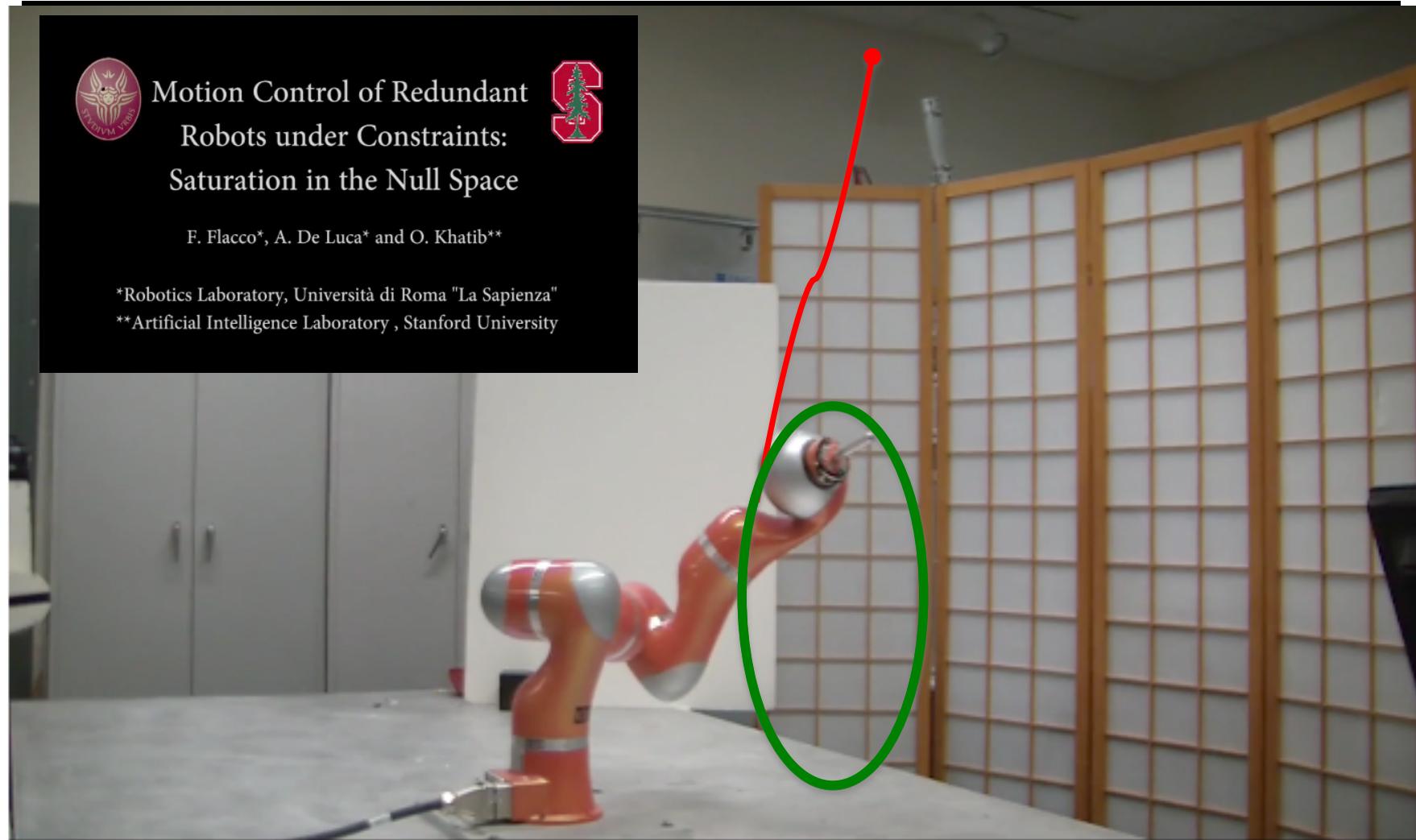
Sneak preview of videos follows ...

- 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



Motion Control of Redundant
Robots under Constraints:
Saturation in the Null Space



F. Flacco*, A. De Luca* and O. Khatib**

*Robotics Laboratory, Università di Roma "La Sapienza"

**Artificial Intelligence Laboratory , Stanford University

KUKA LWR4 robot

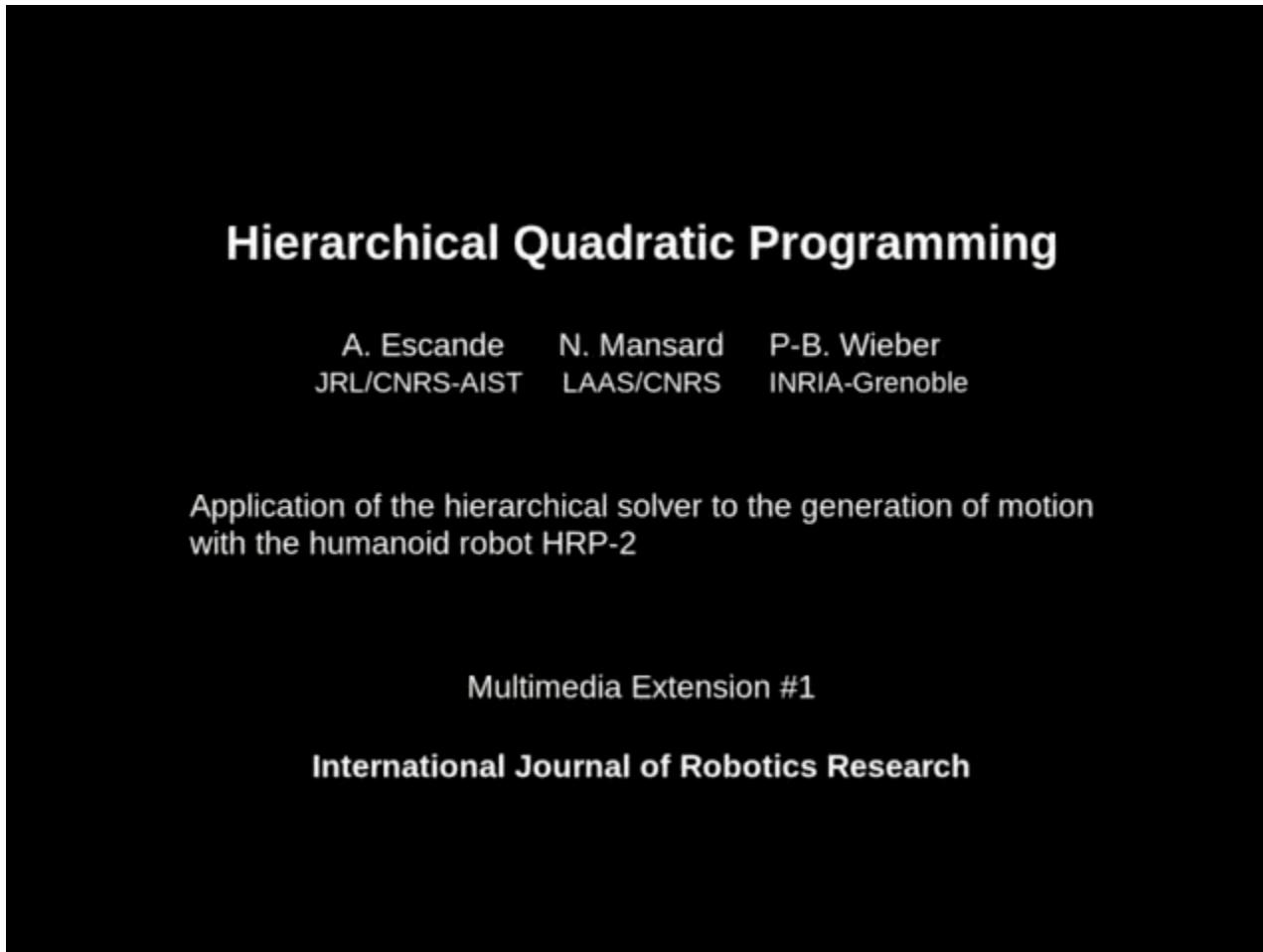
video DIAG Sapienza/Stanford, IEEE ICRA 2012



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



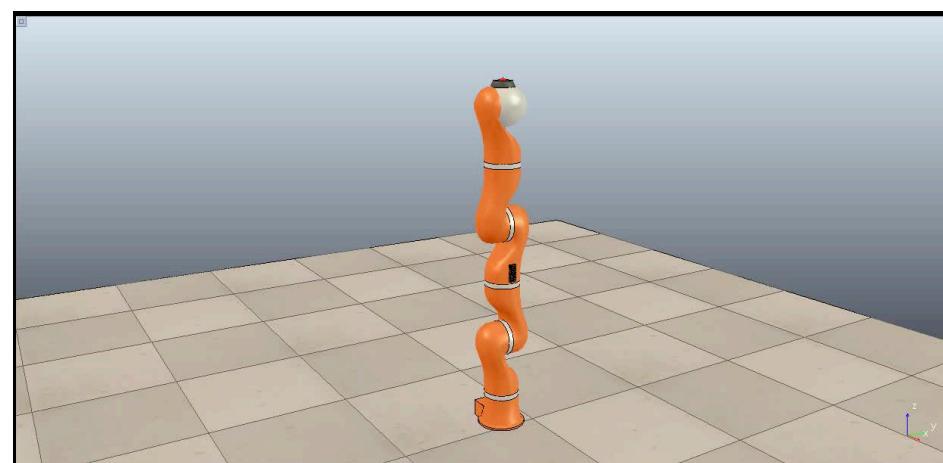
data acquisition
for identification

KUKA LWR4+ robot
with joint torque
sensing



2 videos ICRA 2014 @DIAG Robotics Lab

model validation
by torque prediction



dynamic
simulation
with V-REP

video



Dynamic modeling and identification

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

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

↓

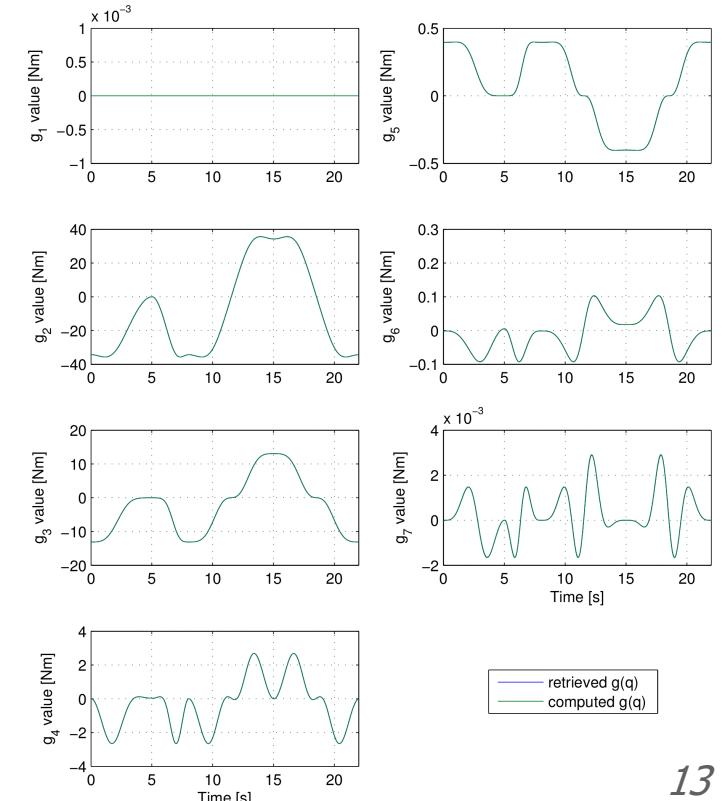
$$\hat{\boldsymbol{\pi}}_g = \begin{pmatrix} 9.5457 \times 10^{-4} \\ -2.9826 \times 10^{-4} \\ 8.3524 \times 10^{-4} \\ 0.0286 \\ -0.0407 \\ -6.5637 \times 10^{-4} \\ 1.334 \\ -0.0035 \\ -4.7258 \times 10^{-4} \\ 0.0014 \\ 9.4532 \times 10^{-4} \\ 3.4568 \end{pmatrix}$$

numerical values identified through experiments

gravity joint torques prediction/evaluation on new validation trajectory

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

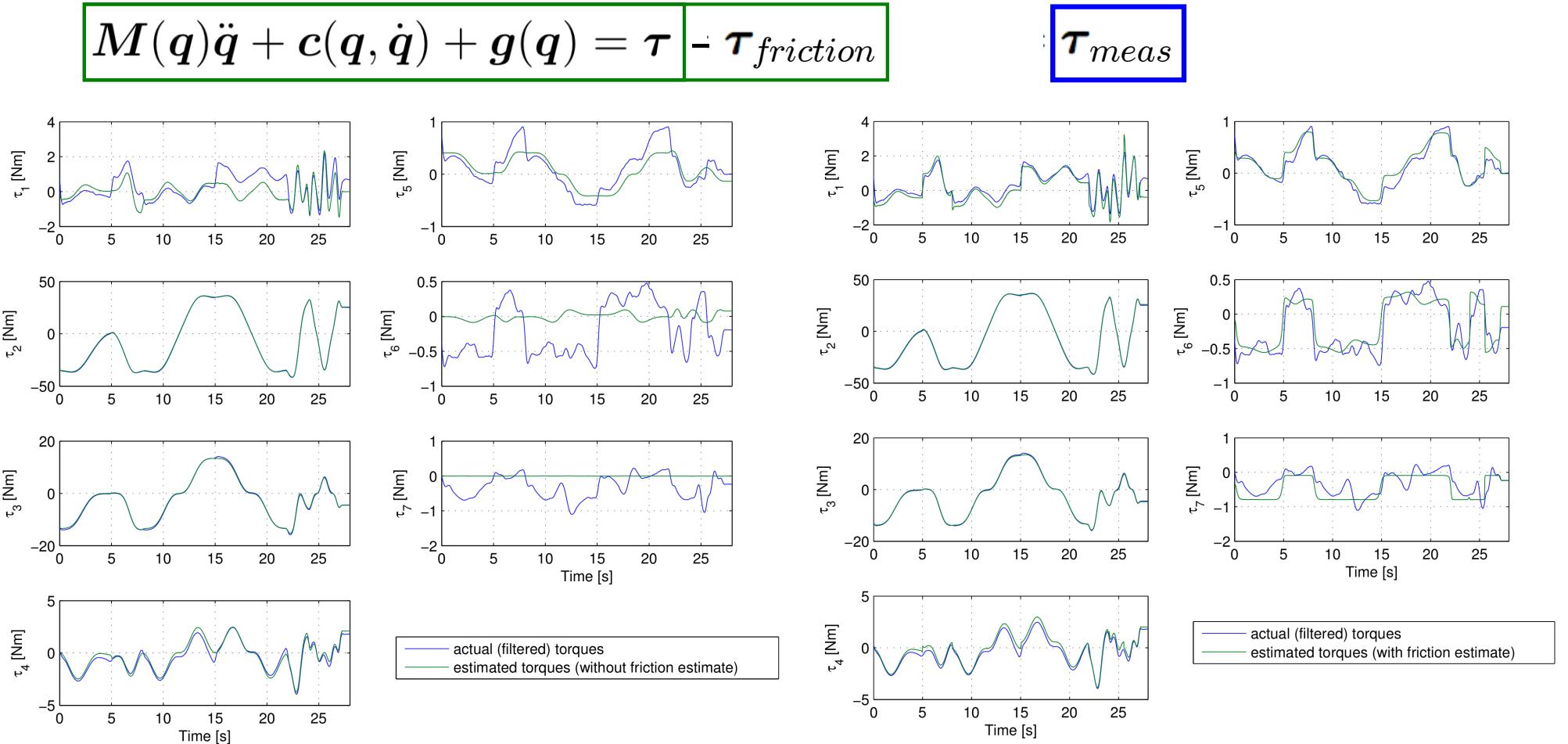
symbolic expressions of gravity-related dynamic coefficients





Dynamic modeling and identification

complete dynamic model estimation vs. joint torque sensor measurement



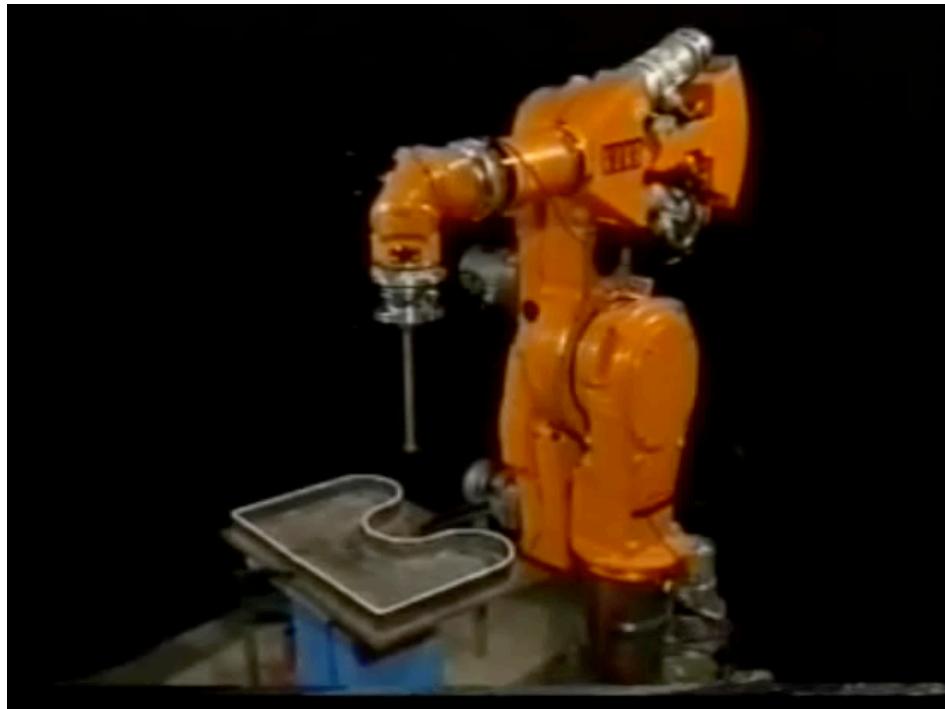
without the use of a joint friction model

including an identified joint friction model



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

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**
(behavior selective in directions)



Motion control with VSA



modular, low-cost
qbmove units

3 videos
@University of Pisa

compliant motion with Variable Stiffness Actuators

Sensorless collision detection

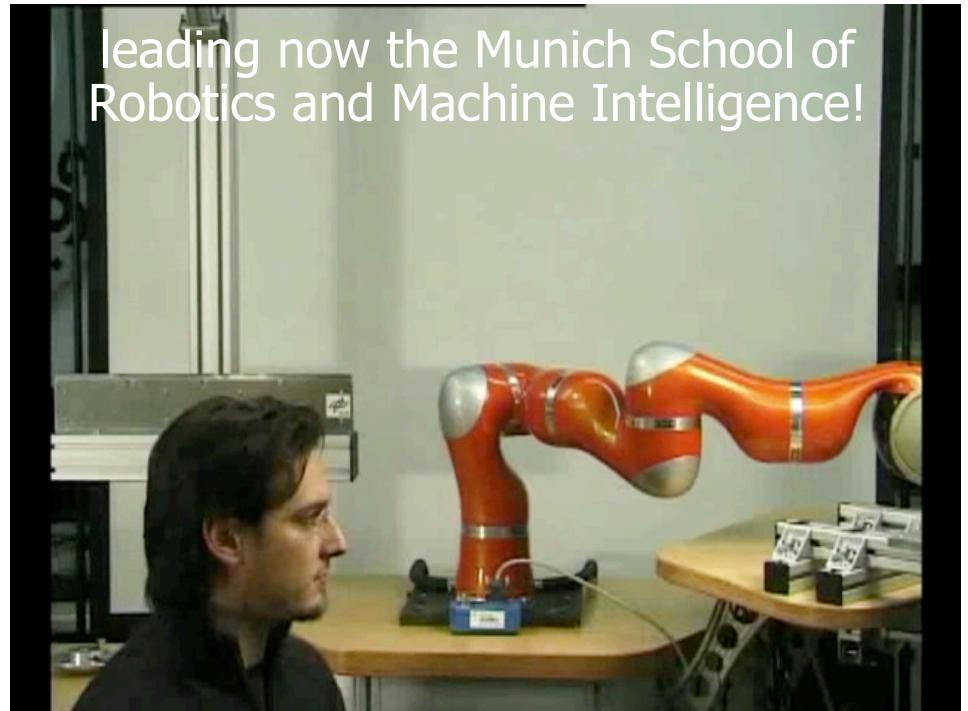


2 videos @DLR München

during my sabbatical in 2005-06



master student Sami Haddadin in 2006



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

NEVER DO THIS!
(unless you're 100% sure of your research results ...)



Safe human-robot collaboration

finalist video IROS 2013 @DIAG Robotics Lab



Safe Physical Human-Robot Collaboration

Fabrizio Flacco Alessandro De Luca

Robotics Lab, DIAG
Sapienza Università di Roma

March 2013



Physical human-robot interaction control

video ICRA 2015 @DIAG Robotics Lab



Control of Generalized Contact Motion and Force in Physical Human-Robot Interaction

Emanuele Magrini, Fabrizio Flacco, Alessandro De Luca

Robotics Lab, DIAG
Sapienza Università di Roma

September 2014



Some recent EU research projects

- FP7 SAPHARI (2011-15)
 - Safe and Autonomous Physical Human-Aware Robot Interaction
 - www.saphari.eu
- H2020 SYMPLEXITY (2015-18)
 - Symbiotic Human-Robot Solutions for Complex Surface Finishing Operations
 - www.symplicity.eu
- H2020 COMANOID (2015-18)
 - Multi-Contact Collaborative Humanoids in Aircraft Manufacturing
 - comanoid.cnrs.fr





Contacts

- office hours
 - Tuesday 12:00-13:30 c/o **A-210**, left wing, floor 2, **DIAG**, Via Ariosto 25
 - .. and/or by email (with some advance)
 - look at the tab “My travel dates” on my web site
- communication by email
 - deluca@diag.uniroma1.it
 - please **check/add your address** in my Robotics 2 mailing list
- URL: <http://www.diag.uniroma1.it/deluca>
- video channel: <http://www.youtube.com/user/RoboticsLabSapienza>
- course material (lecture slides, videos, written exams, ...)
 - http://www.diag.uniroma1.it/deluca/rob2_en.html
 - lecture slides ready (*will be updated during the course*)
- registration to exams in infostud (code 1021883)



Exams and Master Thesis

- type of exam
 - classroom midterm test (**qualifies** for final project)
 - written test + oral part (**or** final project + oral presentation)
- schedule for academic year 2019/20 (already in infostud)
 - **2 sessions** at the end of this semester
 - June 5, 9:00, room B2 and July 15, 9:00, room B2
 - **1 session** after the summer break
 - September 11, 9:00, room B2
 - **2 extra sessions only for students of previous years, part-time, etc.**
 - in April (between 15 and 21) and in October 2020: times/rooms tbd
 - **2 sessions** at the end of the first semester of next year
 - January and February 2021
 - **registration** in infostud, up to **one week before!**
- master theses
 - available at DIAG Robotics Lab: <http://www.diag.uniroma1.it/labrob>