Robotics 1

Introduction

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DIPARTIMENTO DI INGEGNERIA INFORMATICA
AUTOMATICA E GESTIONALE ANTONIO RUBERTI

SAPIENZA
UNIVERSITÀ DI ROMA

Robotics 1 – 2025-26

- First semester
  - Wednesday, September 24, 2025 – Friday, December 19, 2025
- Courses of study (those having Robotics 1 mandatory or as optional)
  - Master in Artificial Intelligence and Robotics (MARR)
  - Master in Control Engineering (MCER)
- 6 Credits
  - ~50 hours of lectures, exercises, and midterm test
  - 90 hours of individual study
- Classes (room B2, DIAG, Via Ariosto 25)
  - Wednesday 15:00-17:00
  - Friday 8:00-11:00

Organization and contacts

all hyperlinks in red are active in my pdf files

- G-group
  - join robotics1_2025-26
    - your **full name**, uniroma1 email, course of study & year (1,2,..)
  - please ask questions & comment on my replies (everyone will benefit!)
- Email deluca@diag.uniroma1.it (personal or private matters)
- Office hours for students
  - Tuesday 12:00-13:30 (check exceptions, e.g., when I'm on travel)
  - in presence: Room A-210, floor 2, left wing, DIAG, Via Ariosto 25
  - remote: Zoom (or Meet), see www.diag.uniroma1.it/deluca/Teaching.php

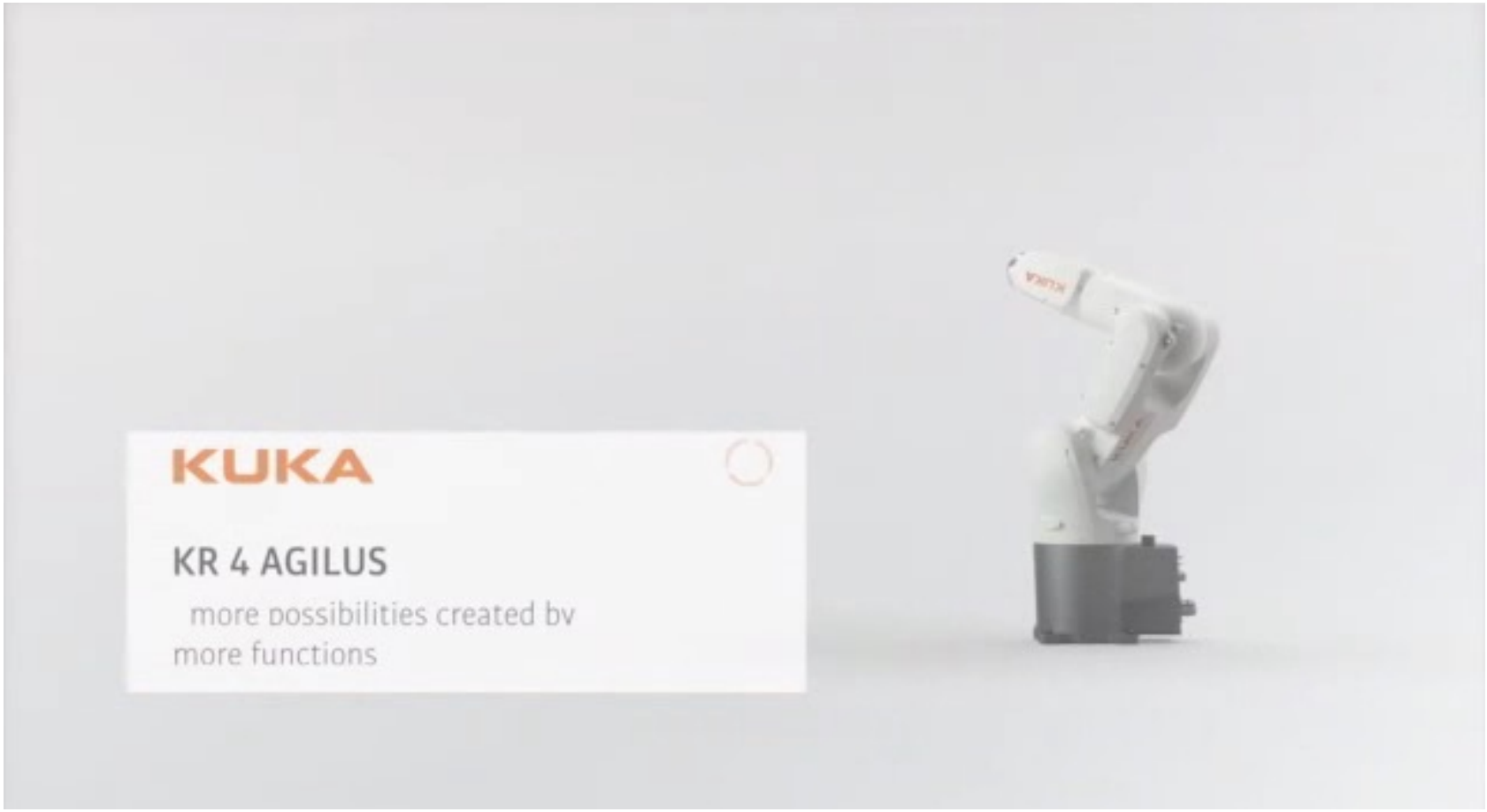
General information

- Prerequisites
  - self-contained course, without special prerequisites
  - background knowledge of kinematics (of a point, of a single rigid body) and linear algebra (vectors and matrices)
  - basics on feedback control (of linear systems) is useful
- Aims
  - robot "anatomy"
  - provide tools for kinematic analysis of articulated chains of multiple rigid bodies (= robot manipulators)
  - analytical methods for planning motion trajectories
  - motion commands and control algorithms
  - programming of tasks for industrial & service manipulators

A robot manipulator

Illustrating typical features of an industrial robot

commercial video



KUKA KR 4 Agilus robot with 6 revolute joints

Robot in action

Universal Robots UR-10

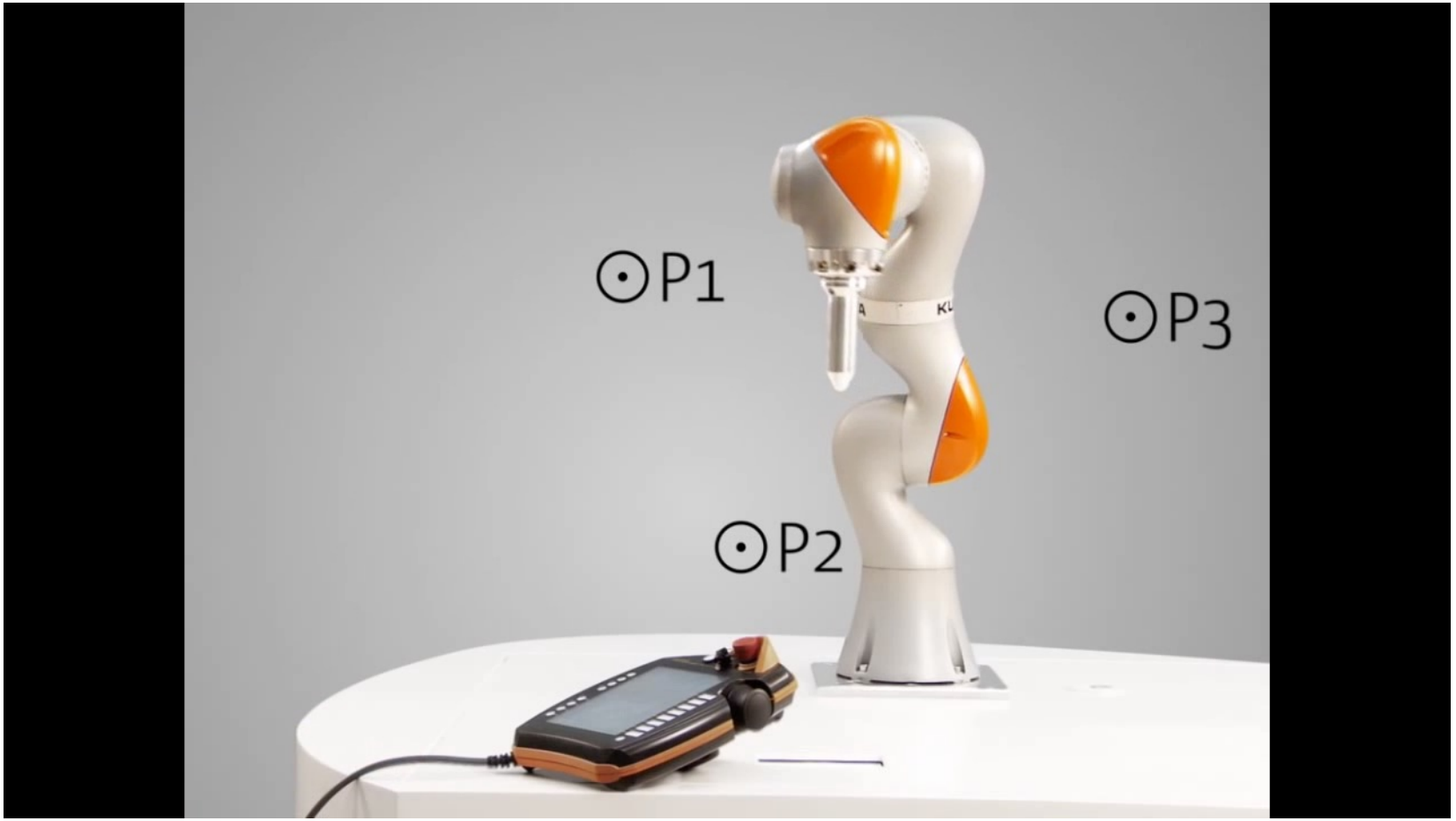
commercial video

1. Pick-and-place on factory floor 2. CNC Machine loading 3. Palletizing egg-boxes
4. Automation in biomedical lab 5. Surface polishing (with prescribed contact force)
6. Quality control 7. Assembly 8. Robot in a cell
9. Base mounting from the top 10. Pick-and-place on conveyor belt

Programming robot motion

Teaching Cartesian poses and playing them back

video

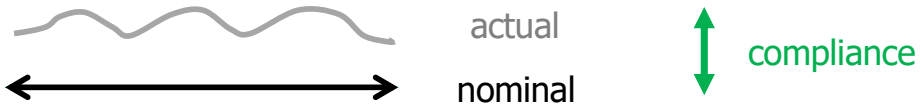


KUKA LBR iiwa robot with 7 revolute joints

Programming robot motion

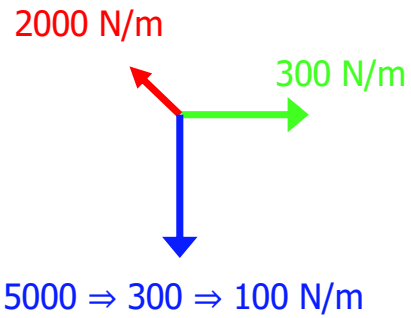
Executing nominal trajectories and "complying" with uncertainties

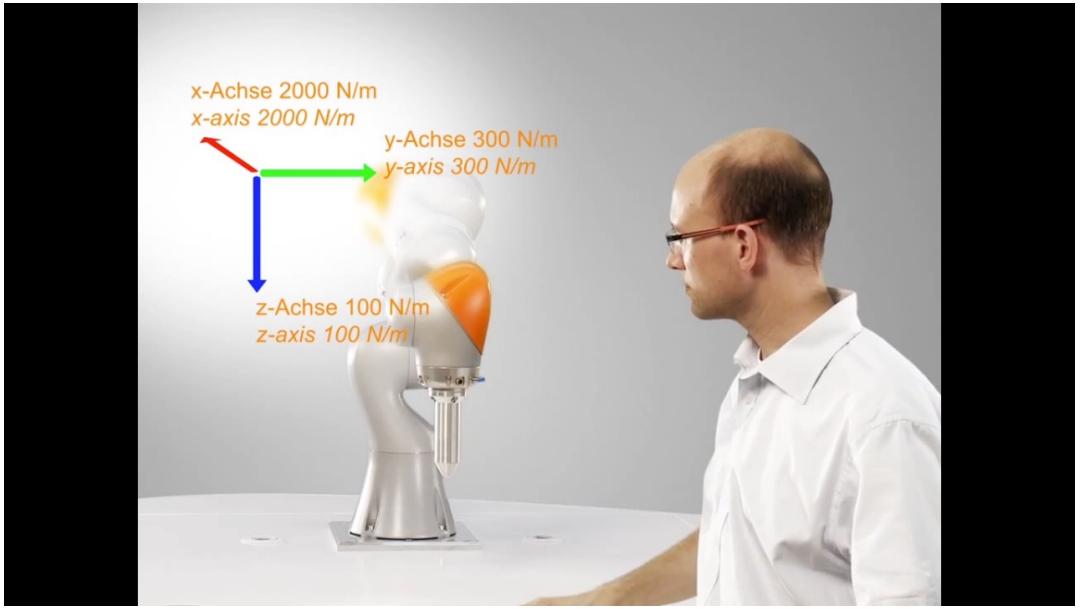
video



Programming robot compliance

Controlled reaction to applied forces/torques at robot end-effector





video

units
$[\mathrm{N/m}]$

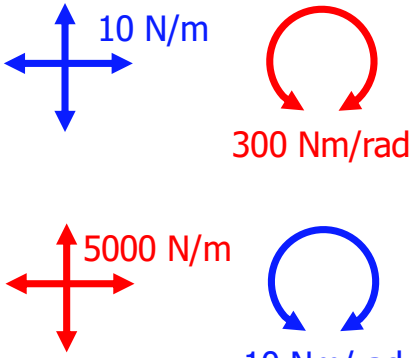
$$\Delta p \rightarrow F = K\,\Delta p$$

stiffness

vs

compliance

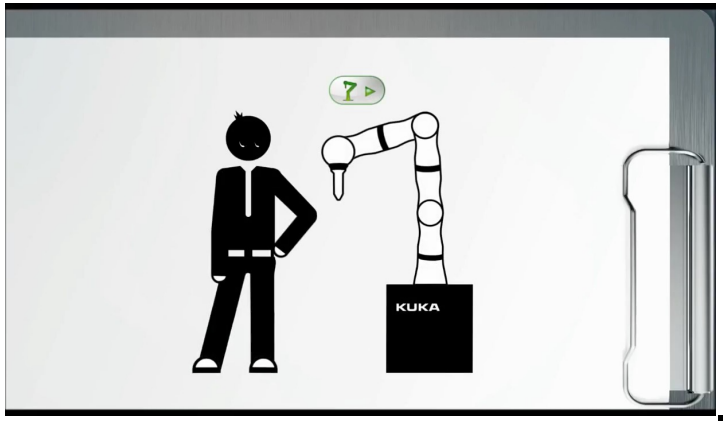
$$F \rightarrow \Delta p = C\,F = \frac{1}{K}\,F$$



video

Programming robot motion

Teaching tasks by demonstration (kinesthetic learning)

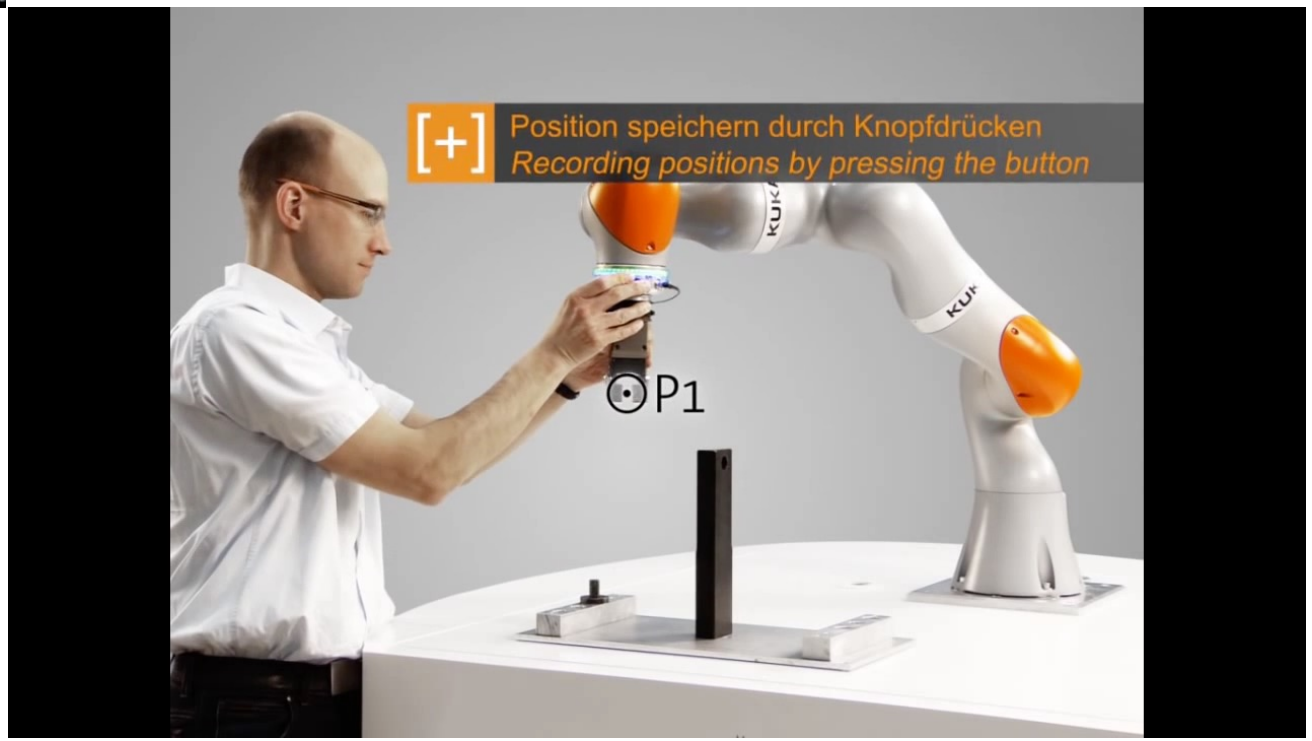


video

sketch of the original idea
— a possible use of safe physical Human-Robot Interaction (pHRI)

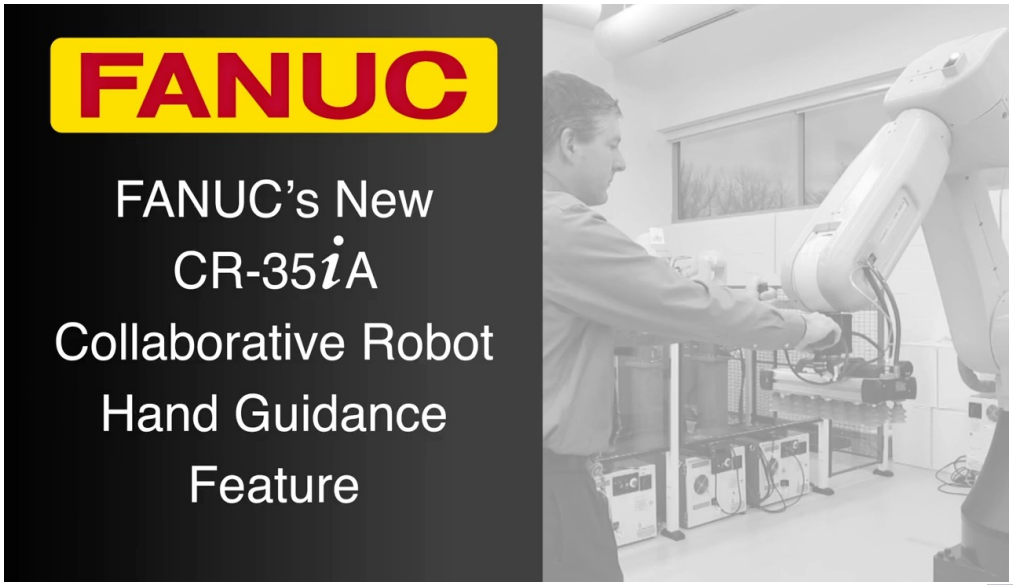
video

the working industrial solution



more videos on
KUKA Robotics YouTube Channel

Industrial vs. service robots



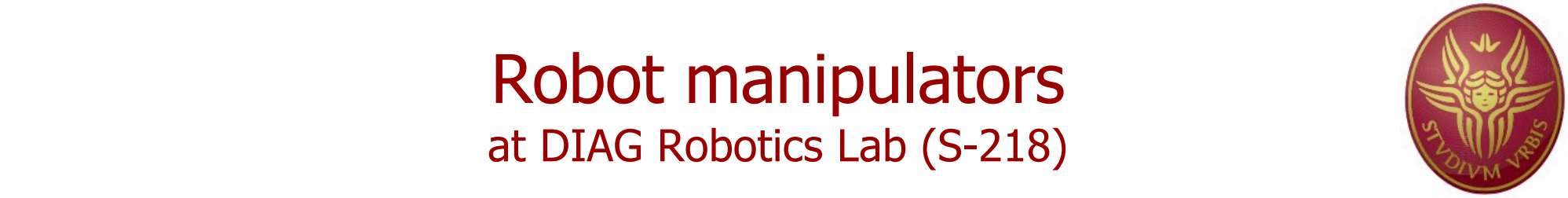
FANUC CR35i 6R collaborative robot carrying up to 35 kg of payload, with hand guidance system

video

video

qbrobotics SoftHand2
dexterous robot hand
with only 2 motors on board
and compliant transmissions
(based on human hand synergies)

Robot manipulators
at DIAG Robotics Lab (S-218)



3 videos

KUKA KR-5
(small size, industrial)

KUKA LWR4+
(lightweight, about 14 kg)

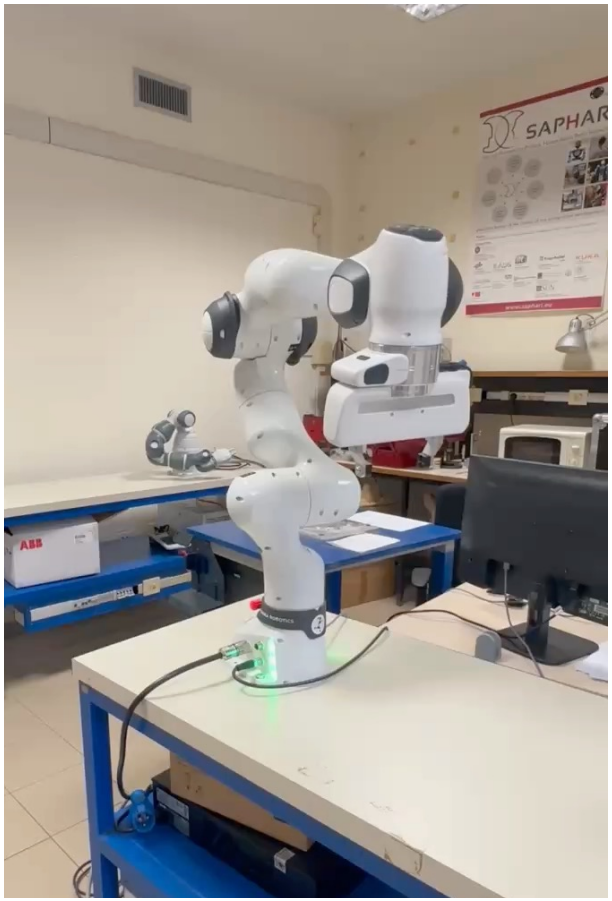
Universal Robots UR-10
(= 10 kg of payload)

New collaborative robots
at DIAG Robotics Lab (S-218)

video

motion and interaction programs in C++/Python

equipped with joint torque sensors



7R Franka Emika R3

(two) 7R ABB YuMi

video

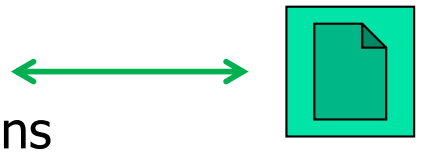
motion and interaction programs in ABB Rapid or C++/Python

DIAG Robotics Lab YouTube channel for more of our research videos

www.youtube.com/user/RoboticsLabSapienza

Program

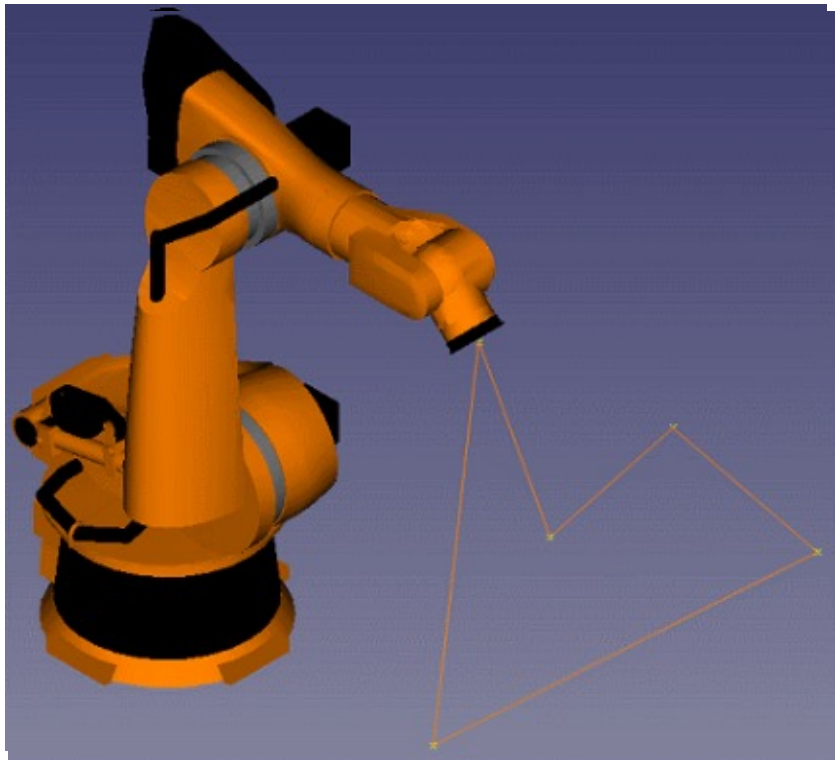
- Introduction
  - Manipulator arms (+ some on a mobile base)
  - Industrial and service applications
- Components
  - Mechanical structures
  - Actuators and transmissions
  - Sensors
    - proprioceptive (encoders, velocity reconstruction, …)
    - exteroceptive (force/torque, depth, vision, infrared, ultrasound, laser)
- Kinematic models
  - Representations of orientation (rotation matrices, Euler angles, ...)
  - Direct and inverse kinematics of robot manipulators
    - Denavit-Hartenberg formalism for frame assignment
  - Differential kinematics: analytic and geometric Jacobians
  - Statics: Transformations of forces
  - Robot singularities



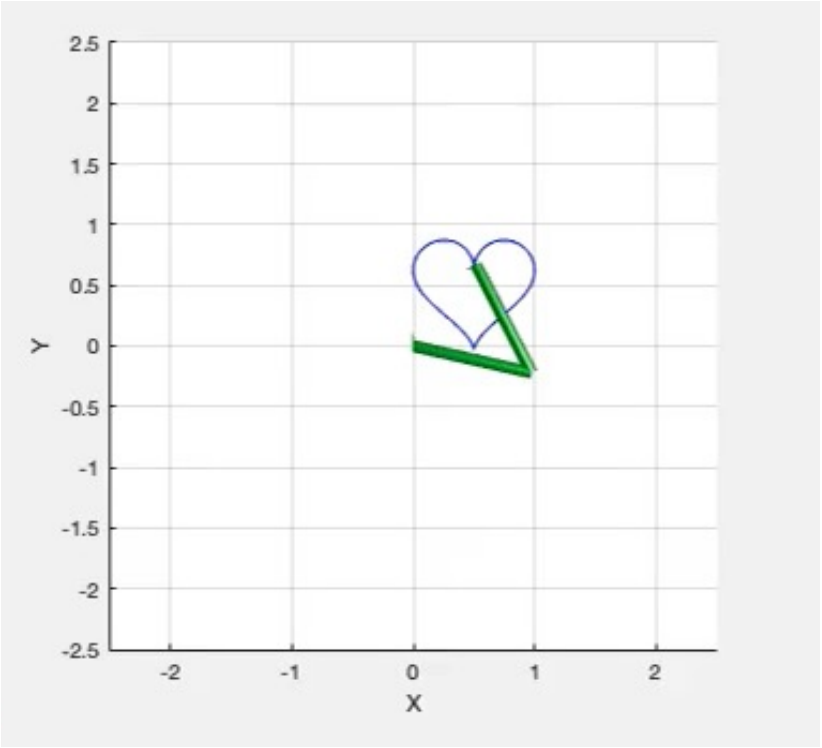
Program (continued)

- Planning of motion trajectories
  - Trajectory: a geometric path with a timing law
  - Planning in joint space for robot manipulators
  - Planning in task/Cartesian space
- Motion control
  - Control system architectures
  - Kinematic control laws (in joint or in task/Cartesian space)
  - Independent joint axis control laws (P, PD, PID)
- Programming and simulation
  - Programming language for industrial robots (KRL, Rapid)
  - Use of Matlab/Simulink (with Robotics Toolbox) or CoppeliaSim (V-REP)

Planning Cartesian trajectories



KUKA 6R articulated robot



video

2R planar robot

timing law

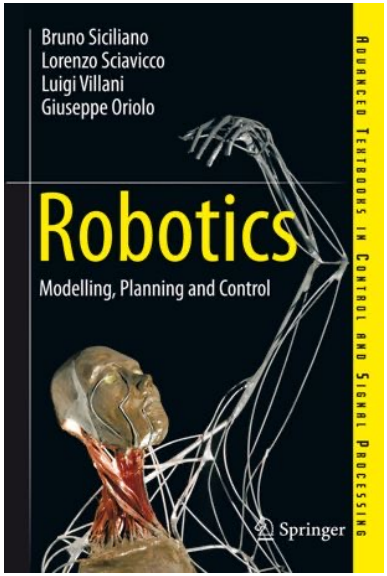
geometric path

```
t = [0:Ts:T]; tau = t/T; s = (-2*tau.^3 + 3*tau.^2); center = [0.5; 0.5];
p = center + [(16*sin(2*pi*s).^3)/16;
              (13*cos(2*pi*s) - 5*cos(4*pi*s) - 2*cos(6*pi*s) - cos(8*pi*s))/16]/2;
```

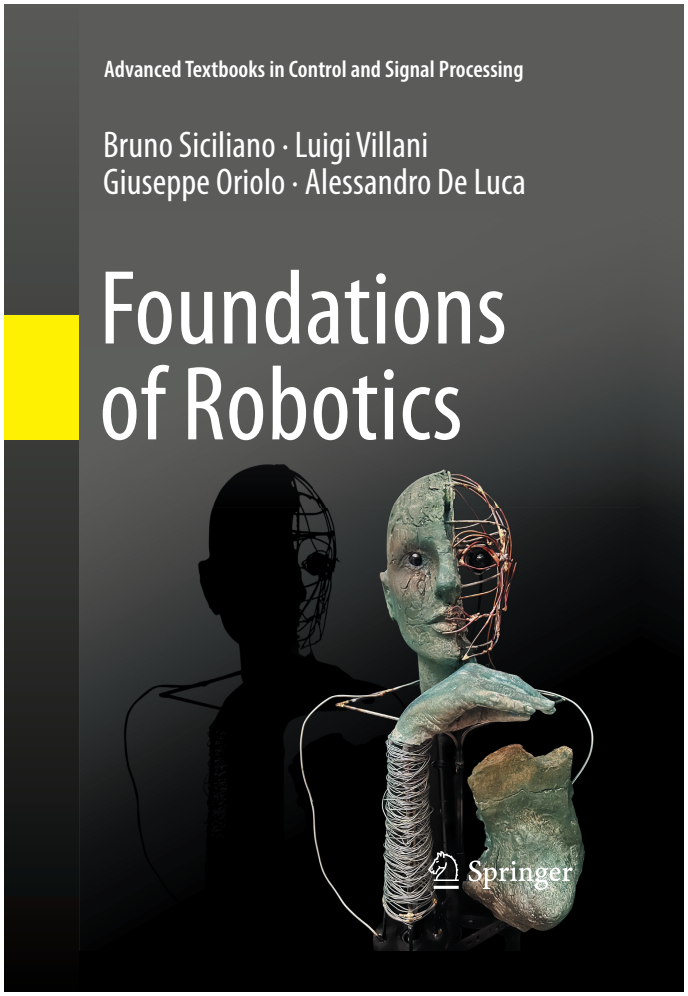
MATLAB code (Diaco & Ficorilli, Sep 2021)

A new textbook!

B. Siciliano, L. Villani, G. Oriolo, A. De Luca: **Foundations of Robotics**, Springer, 2025: https://link.springer.com/book/10.1007/978-3-031-85523-8



worldwide best seller since 2009
(with Italian, Chinese, Greek editions)



published on
September 6, 2025
(eBook, Hardcover, Softcover)

12 chapters
5 appendices
190+ problems
719 pages

Textbook contents
for Robotics 1

some topics will be skipped
(new syllabus in preparation
on course webpage!)

find typos or mistakes
and earn points for the exam!

Other course materials

- Course website www.diag.uniroma1.it/deluca/rob1_en.php
  - pdf of lecture slides ready (with some updates during the course)
  - all videos shown during lectures (in zipped folders by block of slides)
  - written exams (most with solutions), syllabuses, extra documents, …
- Video DIAG channel playlist Robotics 1 with full course of 2014-15
  - 30 (+1 index) videos in classroom (≅ 41h, **>157K** independent views)
- YouTube personal channel: playlists with videos of selected lectures recorded during the pandemic (2019-20 and 2020-21)

Exams and beyond

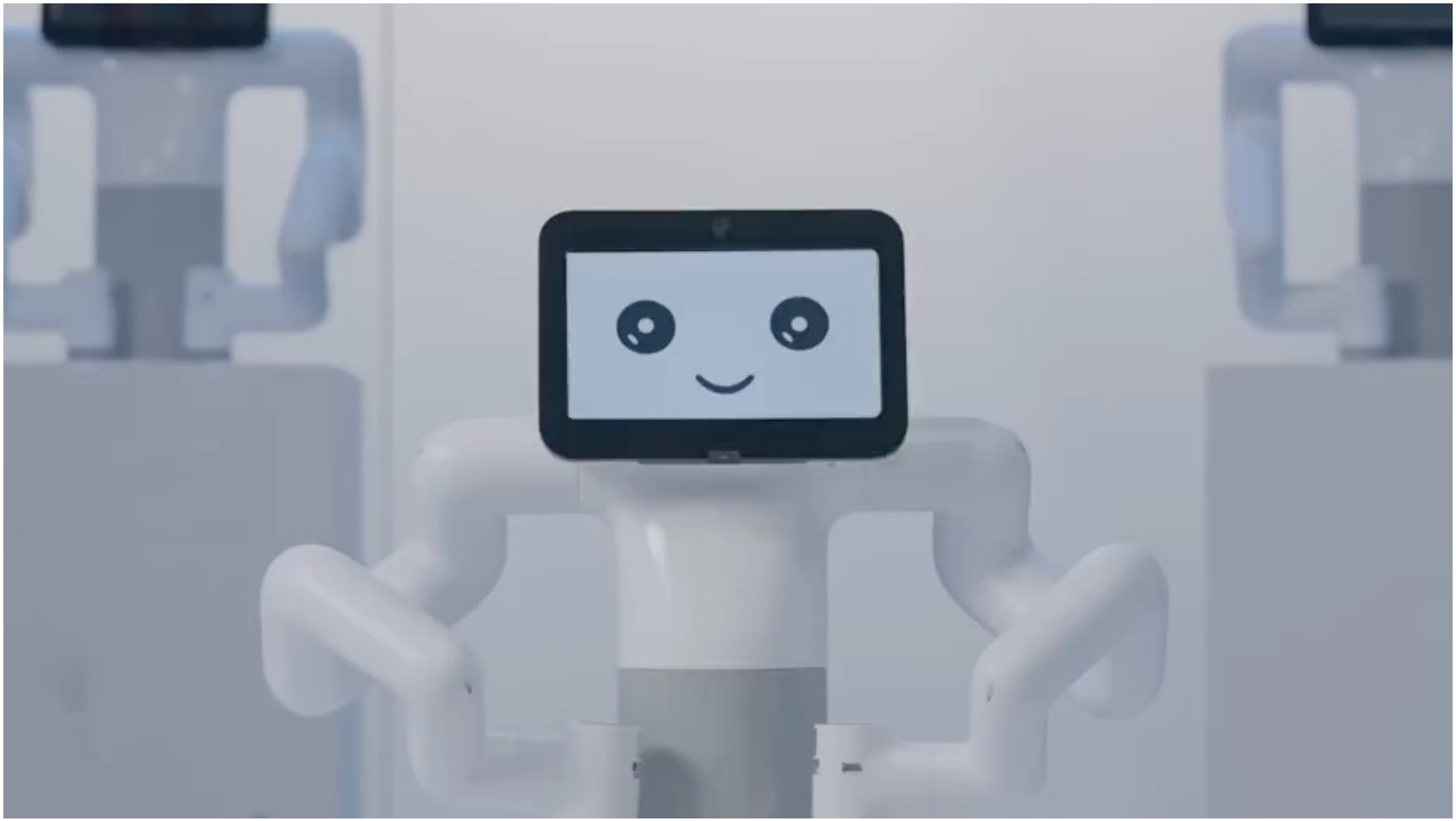
- Type: midterm test (mid November) + written exam (open books)
- Schedule 2025-26
  - 2 sessions at the end of this semester
    - between January 7 and February 20, 2026
  - 2 sessions at the end of next semester
    - between June 3 and July 30, 2026
  - 1 session after the summer break
    - between August 31 and September 22, 2026
  - *2 extra sessions only for students of previous years, part-time, ...*
    - *March 16–April 30 and October 7–November 5, 2026*

will open
on infostud
in early December
check the
course website!

- Signing up to exams
  - on infostud (up to **one week before** the date of the written exam)
- Master theses
  - samples at DIAG Robotics Lab www.diag.uniroma1.it/labrob/theses

Programming motion and behavior

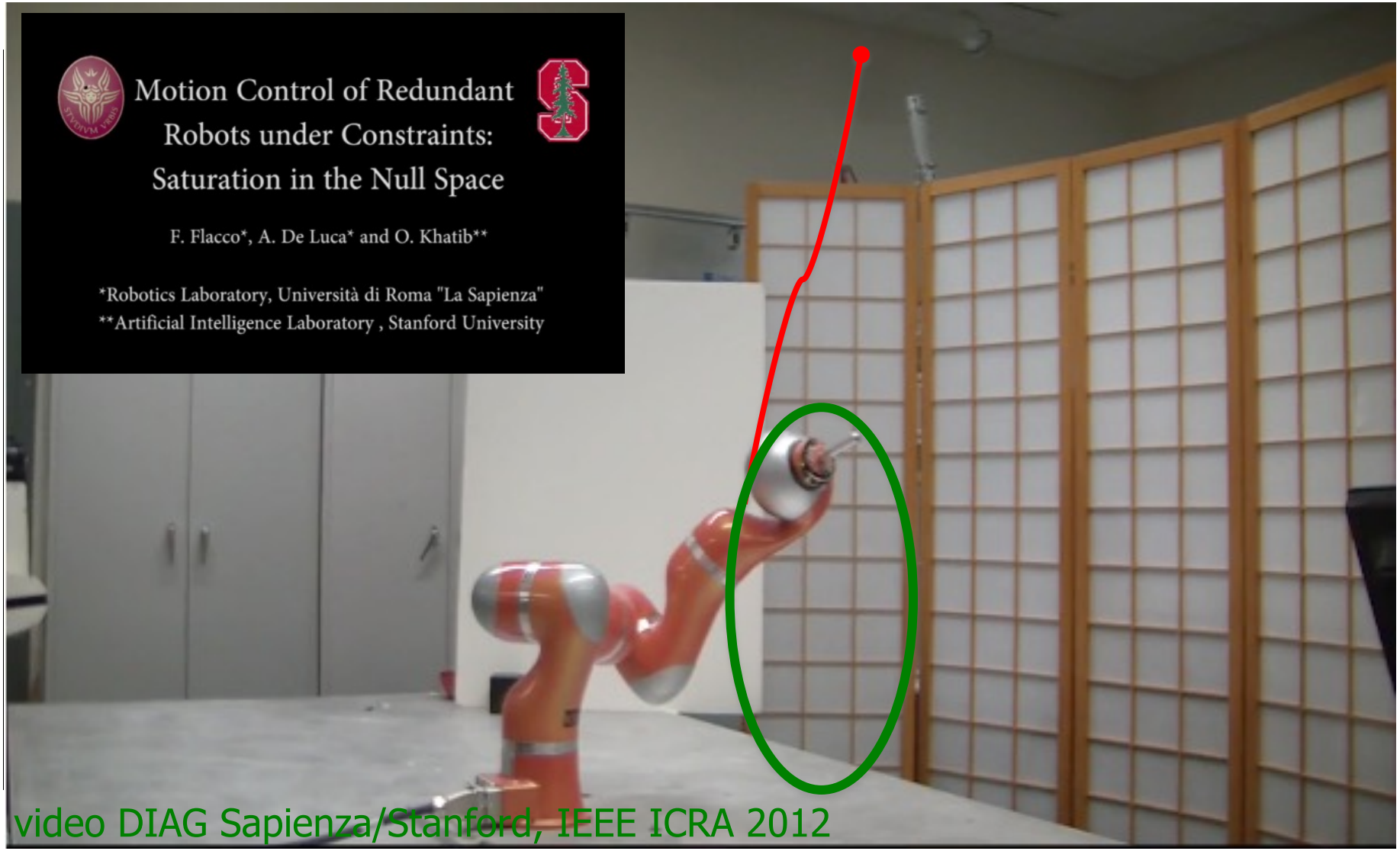
video



myBuddy 280-Pi dual-arm personal robot by Elephant Robotics

Tracking a Cartesian trajectory

with hard position/velocity bounds on robot motion



video DIAG Sapienza/Stanford, IEEE ICRA 2012

Robot control by visual servoing
with limited joint motion range

video INRIA Rennes, IEEE/RSJ IROS 2011

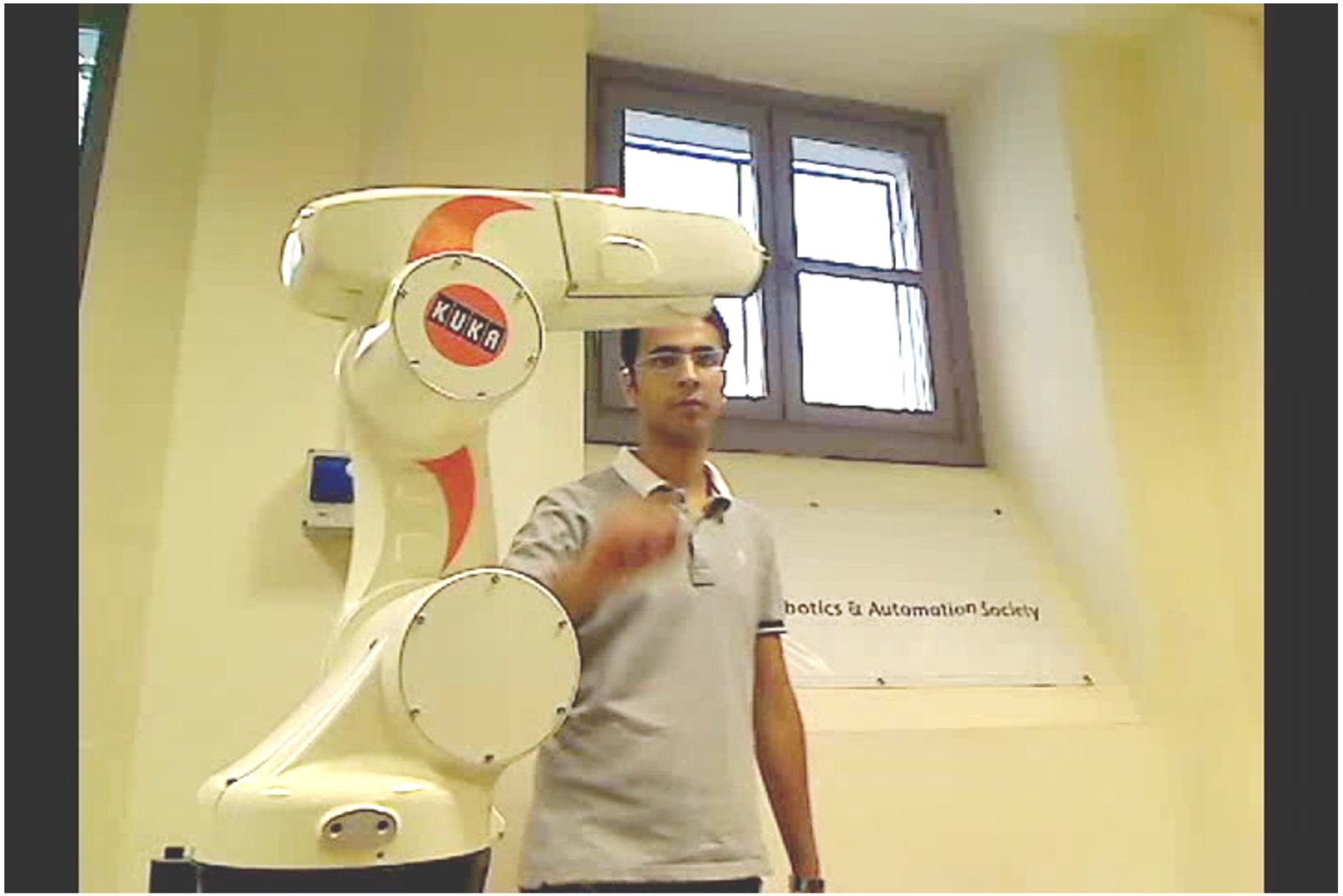
Sensor-based robot control

in dynamic environments (coexistence with human)

video DIAG Sapienza/Stanford, IEEE ICRA 2012

Safe physical human-robot interaction

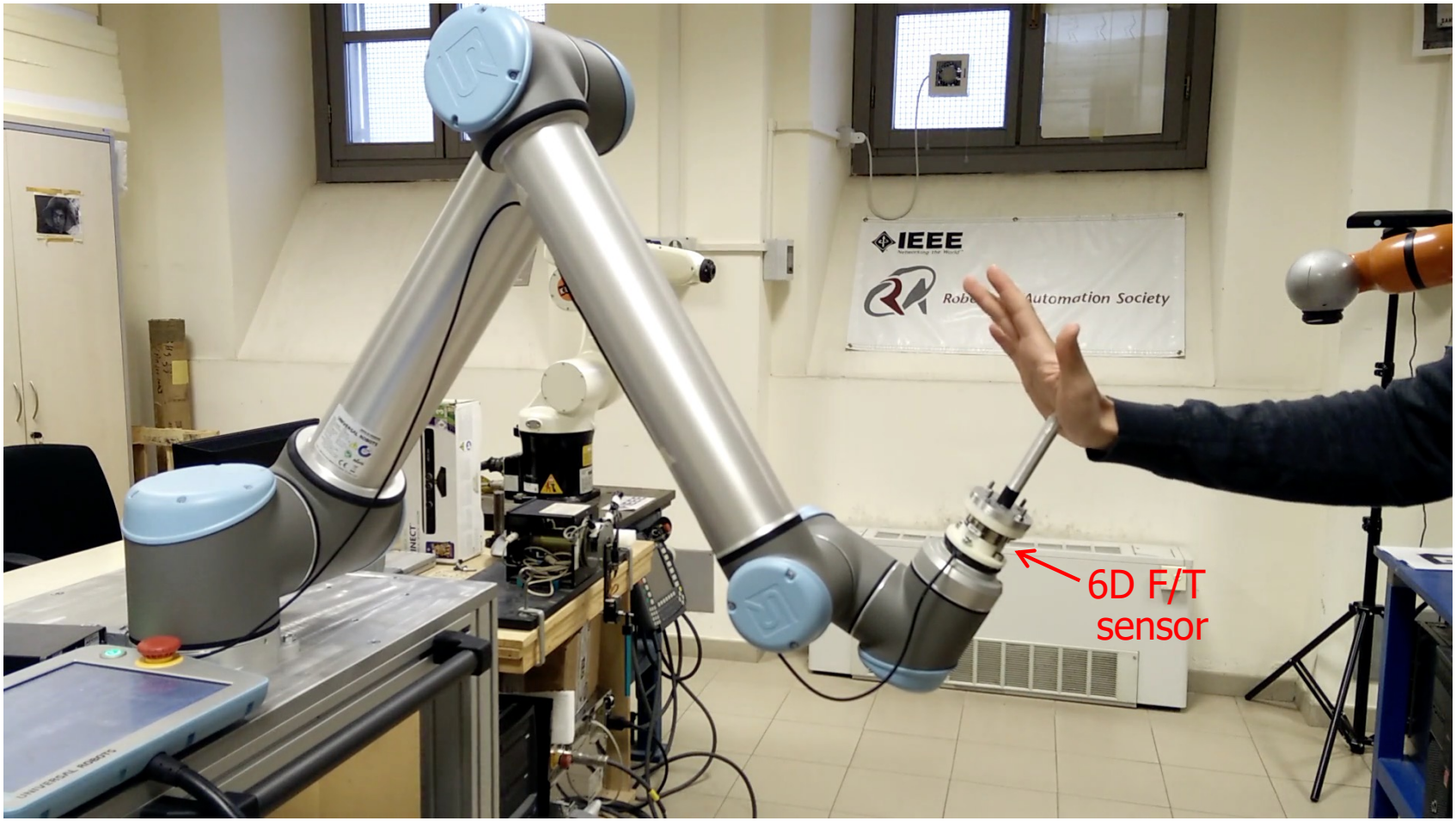
(sensor-less (!) and on a conventional industrial robot)



video DIAG Sapienza, IEEE ICRA 2013

Human-robot collaboration

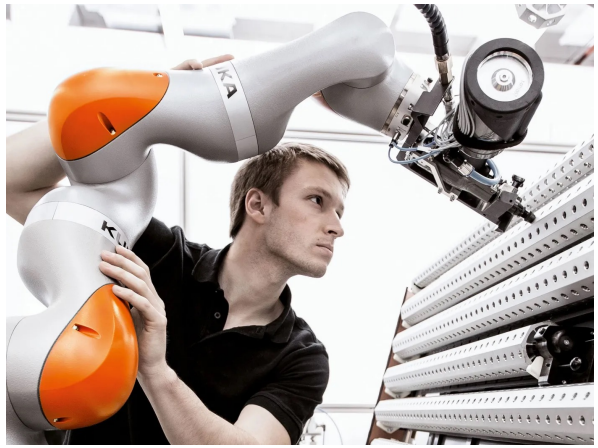
(with a real F/T and "virtual" sensors to distinguish contacts)



video DIAG Sapienza, J. of Mechatronics, 2018

More robots ...

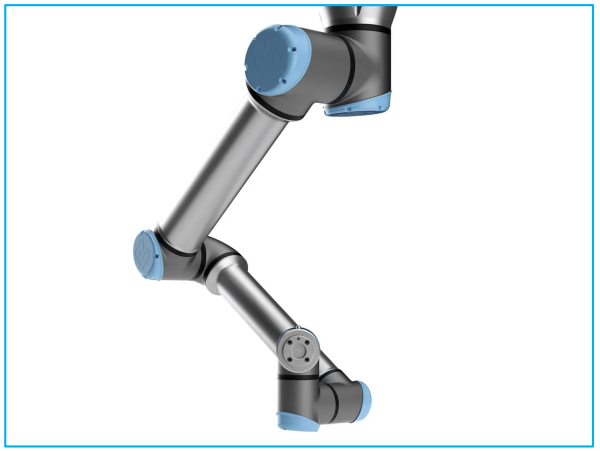
@IEEE https://robotsguide.com



KUKA LBR iiwa
7-dof arm
DE 2013

https://youtu.be/7GdiN6KmGCc

UNIVERSAL ROBOTS
UR5 6-dof arm
DK 2008

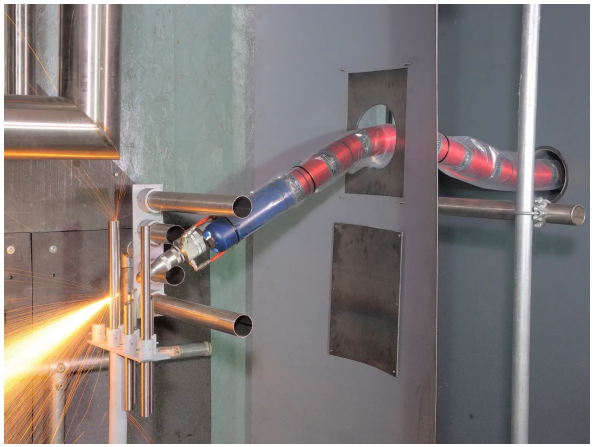


https://youtu.be/UQj-1yZFEZI

ABB YuMi-FRIDA
bi-manual arm
SE-CH 2011

https://youtu.be/70V6J4Y8hnc

OCRobotics Explorer
snake arm
UK 2009

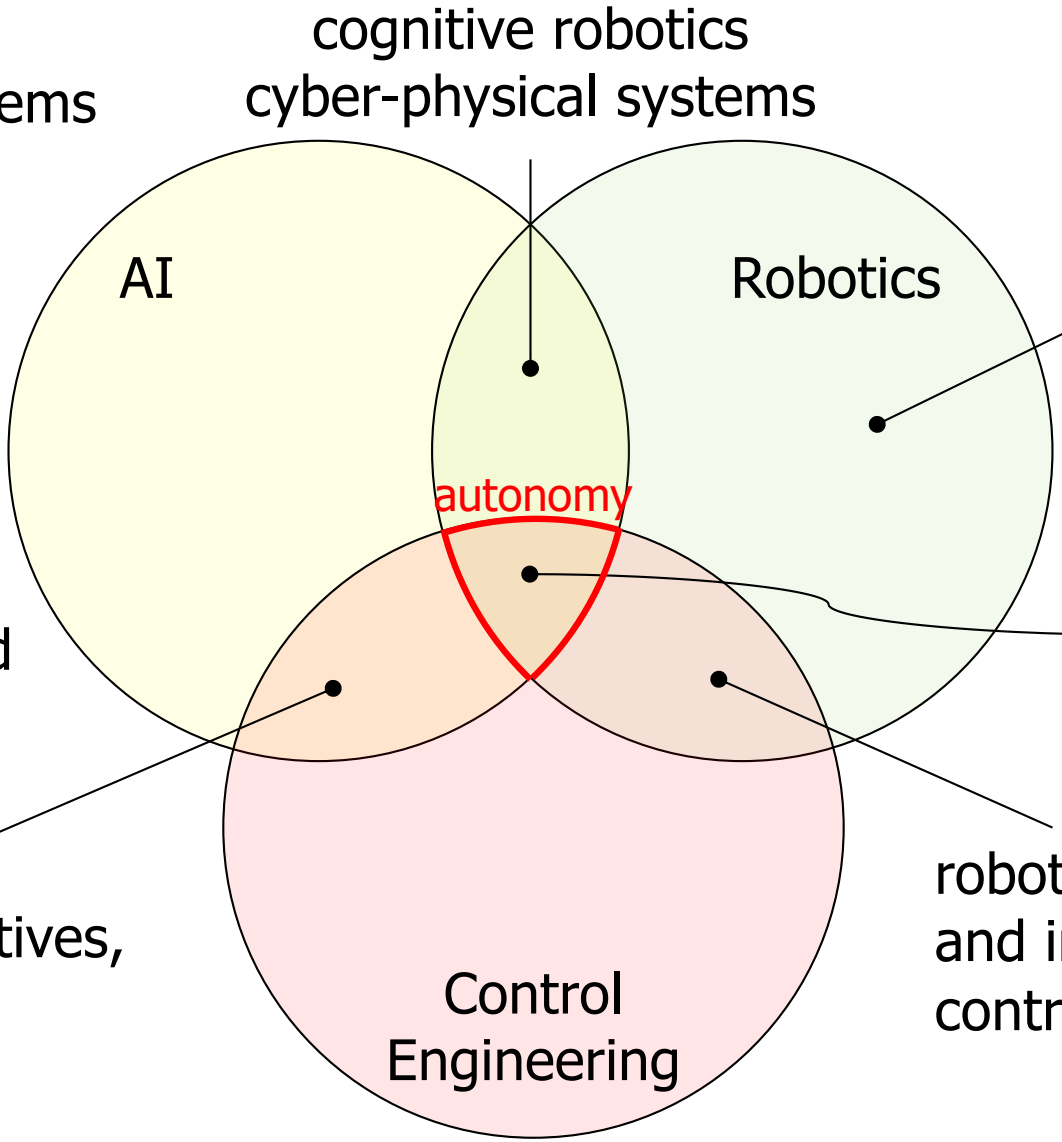


https://youtu.be/_gU6TWGynkU

Next generation of intelligent robots?

Robots =
embodied AI systems

Robotics =
science
of artifacts
intelligently
actuated and
interacting with
the physical world



AI and Robotics

manipulation tasks

Toyota Research Institute
(work by Russ Tedrake)

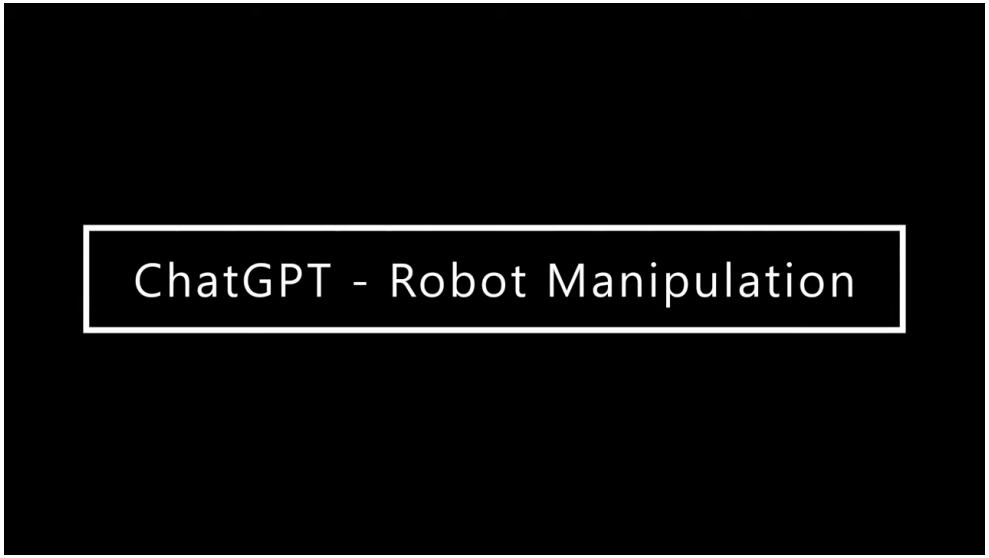
dishwasher loading:
a manipulation task (speeded up!)
that integrates planning, vision,
learning and control

video

video

pick-and-place motion:
programming a manipulation task
from LLM commands
(using a library of motion primitives!)

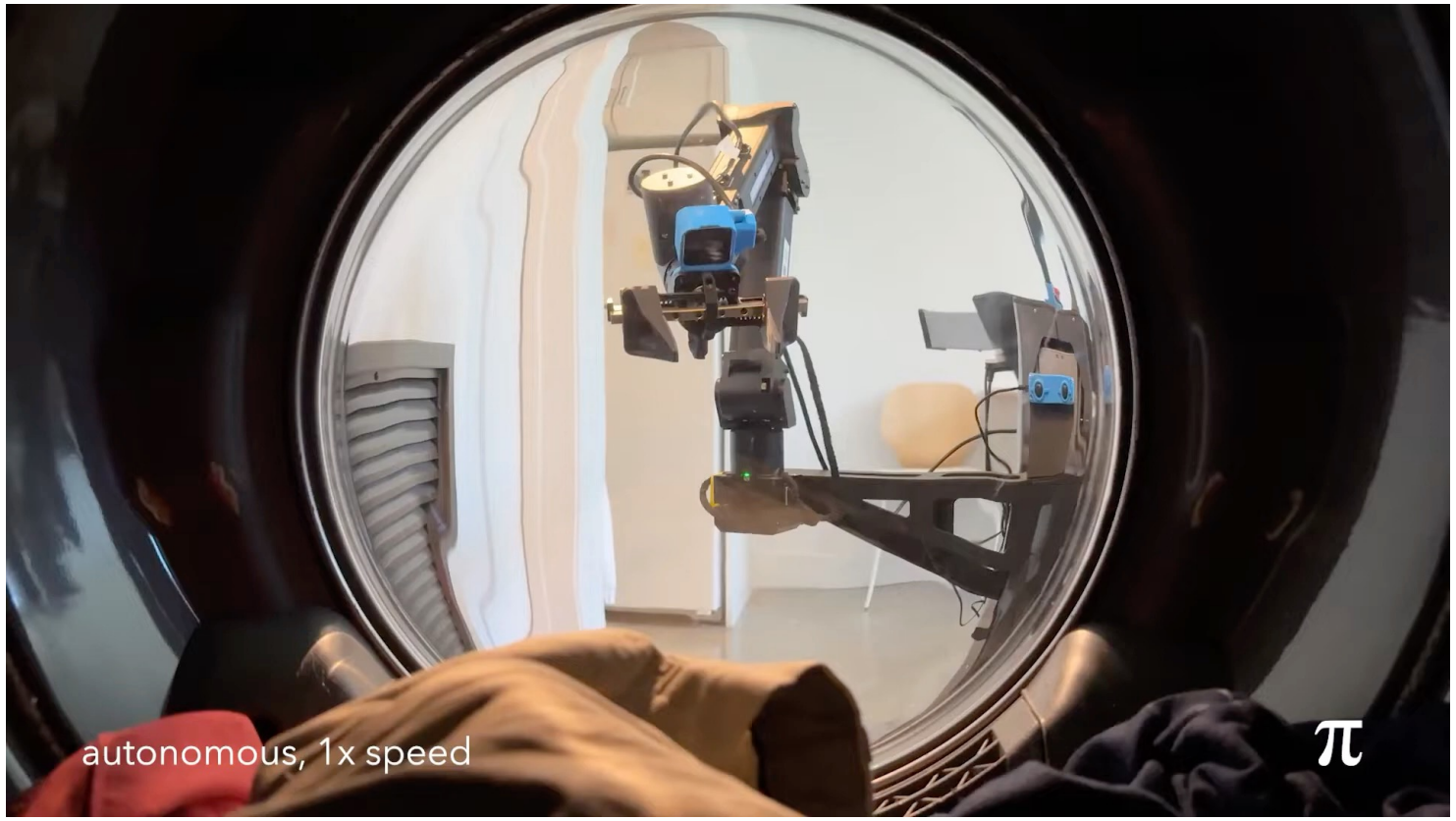
Microsoft
ChatGPT for Robotics



AI and Robotics
foundation models

π_0 by Physical Intelligence (Nov 2024) or RT-X by Google DeepMind (Oct 2023)

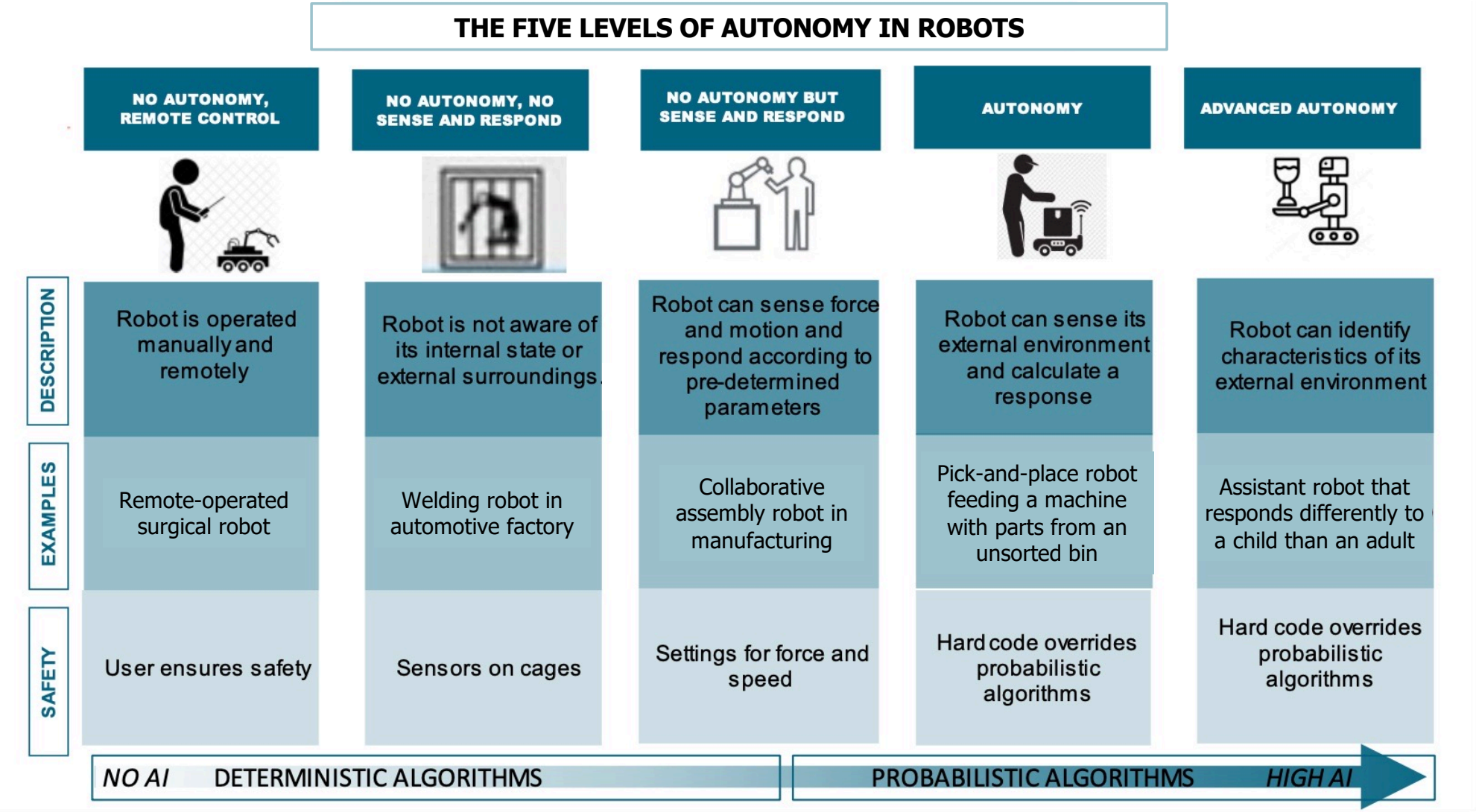
- model trained on broad and diverse data (including text instructions)
- embodied robot experience: learning directly low-level motor commands
- generalization over tasks and robots



video

https://youtu.be/a6Ix6Vzuk0c

Levels of robot autonomy
in industrial applications



source, IFR 2022

Horizon Europe (2021-27)

local link to the document

Cross-Sectorial AI, Data and Robotics Technology Enablers

Sensing and Perception

Knowledge and Learning

Reasoning and Decision Making

Action and Interaction

Systems, Methodologies, Hardware & Tools

Robotics Deep Dive

Physical Interaction

Physical and Psychological Safety

Actuated Mechanical Structures

Unpredictable and Unknown Environments

Irreversible Actions

4 Market Prioritization in Robotics (from Horizon 2020)

Healthcare

Maintenance and Inspection of Infrastructures

Agri-Food

Agile Production

Specific to Robotics

- hard physical/real-world nature of Robotics ("AI embodied")
- wide range of technologies are integrated within robotic systems
- skill mix needed for success is broader than in AI or Data alone
- robots are realizations of advanced system-level concepts
  - such as autonomy, control, sensing, perception and programming
- robots are both producers and consumers of data
  - physical model-based approaches, generation of data-driven models
- decision makers and general public need a better understanding of what Robotics is and can achieve, and how it can be deployed
  - Fukushima, Covid19, Humanoids at home ….

AI & Robotics point of views

example with one of the cross-sectorial technology enablers

one enabling technology

… its relations with the other technologies

	Sensing and Perception	Knowledge and Learning	Reasoning and Decision Making	Systems, Hardware, Methodologies and Tools
Action and Interaction	Depends on sensing of motion and mechanical properties Relies on perception for interaction Uses recognition of actions and sequences of interactions in people	Gets semantic knowledge around objects and human actions Gets data on objects and places	Depends on real-time context-aware decision making Trusted decision making	Depends on fast reactive architectures for control Relies on edge-based AI Requires assurance of safe operation and data privacy

Real-time interpretation of multi-modal data

Safe monitoring in human environments

Active exploration strategies

Adaptive decision-making models from sparse data

Planning and re-planning under uncertainty and incomplete knowledge in dynamic environments

Real-time control (distributed/decentralized)

Safe control of physical human-interaction

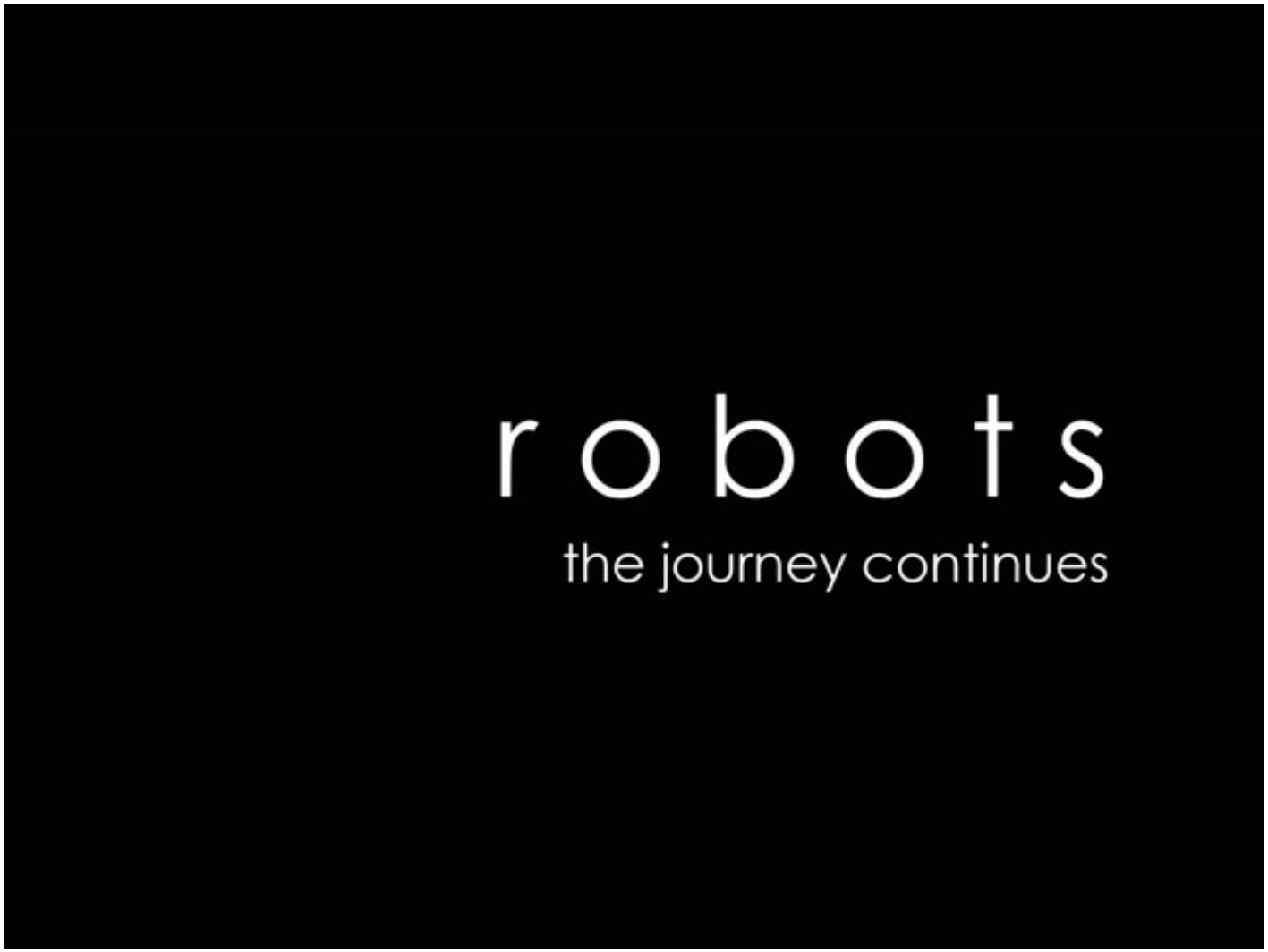
Agility (speed and strength) of collaborative robots

InterAction Technology (lightweight, compliant & soft devices/materials)

Energy-efficient, robust and sustainable design

Robotics around the world...

Springer Handbook of Robotics (2nd Edition, July 2016)



full video on https://vimeo.com/173394878 (free login)

Preview of Robotics 2

6 credits, II semester, year 1

- Advanced kinematics / Robot dynamics
  - Calibration
  - Redundant robots
  - Dynamic modeling: Lagrange and (recursive) Newton-Euler methods
  - Identification of dynamic parameters/coefficients
  - Geometrically constrained dynamics
- Control techniques
  - Free motion linear/nonlinear feedback control, robust control, adaptive control, iterative and online learning
  - Constrained motion admittance, impedance, hybrid force-motion control
  - Visual servoing (kinematic approach)
- Special topic
  - Diagnosis and isolation of robot actuator faults

Textbook contents
for Robotics 2

B. Siciliano, L. Villani, G. Oriolo, A. De Luca: **Foundations of Robotics**, Springer, 2025
https://link.springer.com/book/10.1007/978-3-031-85523-8

more topics are also part of the program
(new syllabus in preparation
on course webpage!)

Other courses on Robotics and Control

- Autonomous and Mobile Robotics (6 credits), I semester, year 2
  - kinematics, planning, control of wheeled and legged mobile robots
  - motion planning with obstacles, navigation, and exploration
  - Prof. Oriolo www.diag.uniroma1.it/oriolo/amr
- Medical Robotics (6 credits), II semester
  - robot surgical systems, haptics, and more ...
  - Prof. Vendittelli www.diag.uniroma1.it/vendittelli/MR
- Elective in Robotics (12 credits) or Control Problems in Robotics (6 credits)
  - I-II semesters, starting this semester
  - 4 modules of 3 credits (for CPR, students take 2 modules out of the 4 in EiR)
  - research-related subjects: e.g., physical robot interaction (with humans, aerial, …)
  - multiple instructors www.diag.uniroma1.it/vendittelli/EIR
- Probabilistic Robotics (6 credits), I semester, year 2
  - Least Squares state estimation, Kalman filter, SLAM
  - Prof. Grisetti sites.google.com/diag.uniroma1.it/probabilistic-robotics-2025-26
- Robot Programming (3 credits, no mark), I semester, year 1
  - robot programming using C++, modules with ROS, embedded real-time coding
  - Prof. Grisetti sites.google.com/diag.uniroma1.it/robot-programming-2025-26

I-RIM conference 2025

Gazometro Roma, 17-19 October 2025

- Institute of Robotics and Intelligent Machines (I-RIM)
  - national association of academic and industrial stakeholders
  - created in 2019
  - check the web site for multiple initiatives: https://i-rim.it/en
- 7th national I-RIM conference
  - scientific presentations, workshops, expo, demos …
  - in conjunction with MakerFaire Europe
  - registration for students is very low
- Student staff is needed!! Contact asap: a.demofonti@unicampus.it

I-RIM