Robotics 1

Introduction

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Sapienza
Università di Roma

Robotics 1 – 2023-24

- First semester
  - Wednesday, September 27, 2023 – Friday, December 22, 2023
- Courses of study (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 17:00-19:00
  - Friday 8:00-11:00

General information

- Prerequisites
  - self-contained course, without special prerequisites
  - elementary knowledge on kinematics, linear algebra, and feedback control 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 command and control algorithms
  - programming of tasks for robot manipulators in industrial and service environments

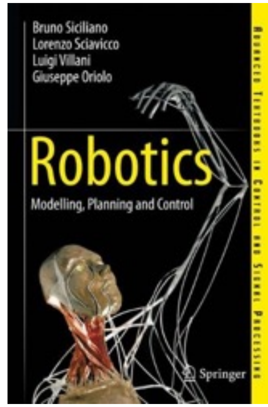
Organization and contacts

all hyperlinks in red
are active in the pdf file

- G-group
  - join robotics1_2023-24 (your **full name**, uniroma1 email, course of study)
  - ask questions, comment on my replies (for the benefit of everyone!)
- Email deluca@diag.uniroma1.it
- 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
- YouTube
  - personal channel: playlists with recorded videos of selected lectures recorded during the pandemic (2019-20 and 2020-21)
  - access restricted to Sapienza students in G-group of the course!

Course materials

- Textbook
  - B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo: *Robotics: Modelling, Planning and Control*, 3rd Edition, Springer, 2009
  - English, Italian, Chinese & Greek editions

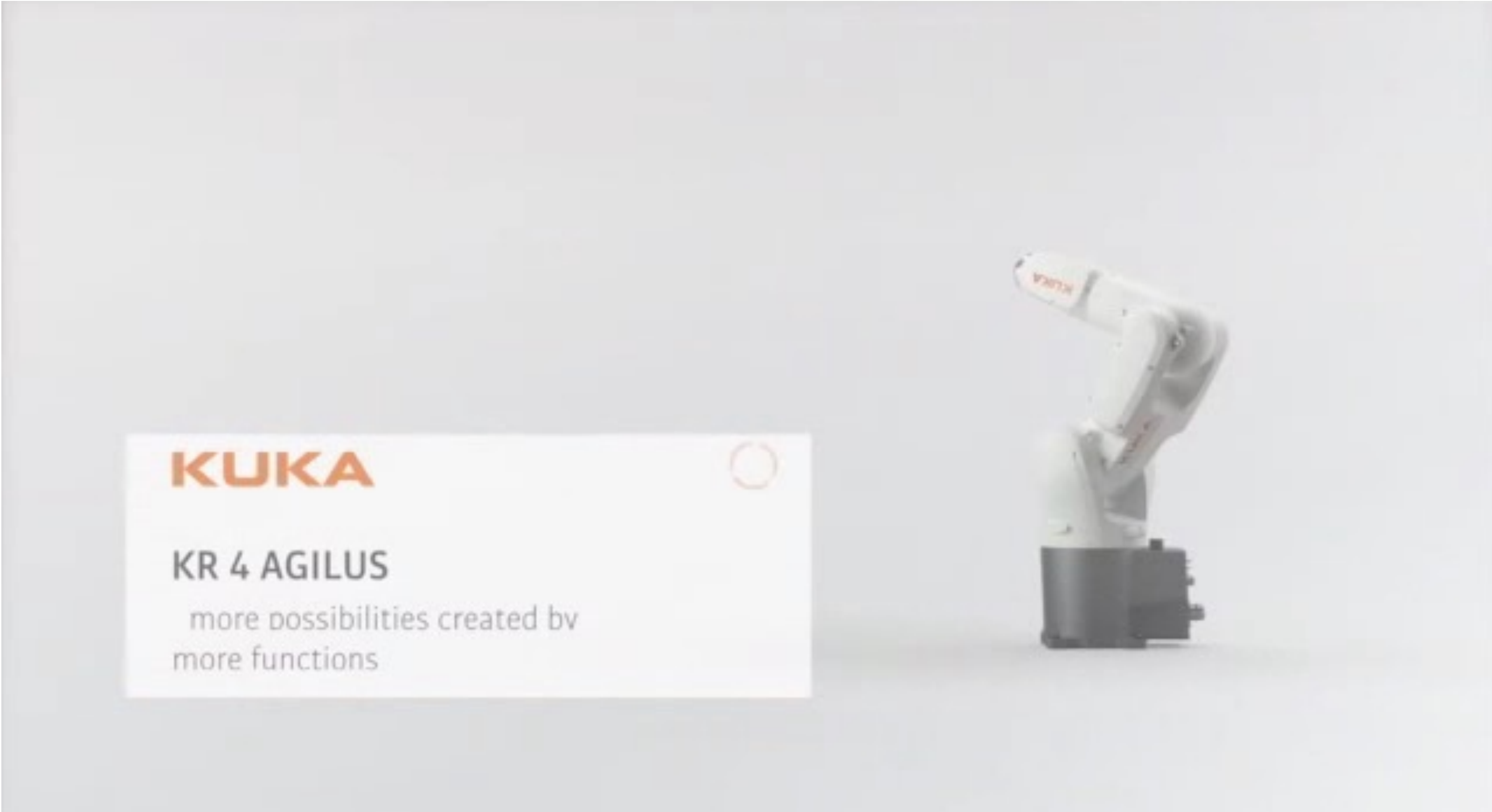


- Course website www.diag.uniroma1.it/deluca/rob1_en.php
  - pdf of lecture slides ready (with some updates during the course)
  - all videos shown during lectures (in zipped folders by block of slides)
  - written exams (most with solutions), syllabuses, extra documents, …
- Video DIAG channel playlist Robotics 1 with full course of 2014-15
  - 30 (+1 index) videos in classroom (≅ 41h, **>125K** independent views)
- DIAG Robotics Lab YouTube channel with more research videos
  - www.youtube.com/user/RoboticsLabSapienza

A robot manipulator

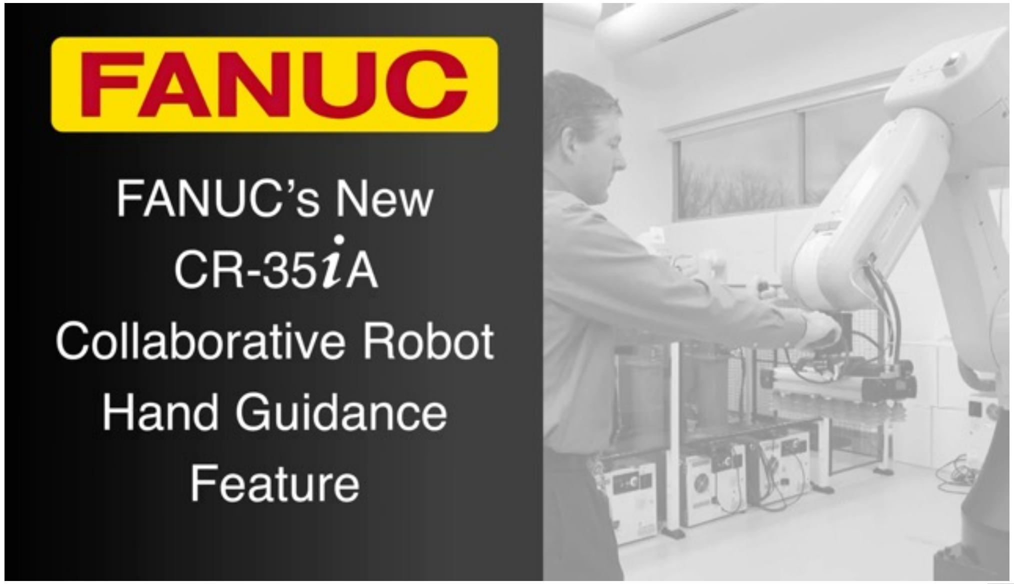
Illustrating typical features of an industrial robot

commercial video



KUKA KR 4 Agilus robot with 6 revolute joints

Industrial vs. service robots



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

video

video

qbrobotics SoftHand2
dexterous robot hand
with only 2 motors on board
and compliant transmissions

Programming robot motion

Teaching Cartesian poses and playing them back

video

KUKA LBR iiwa robot with 7 revolute joints

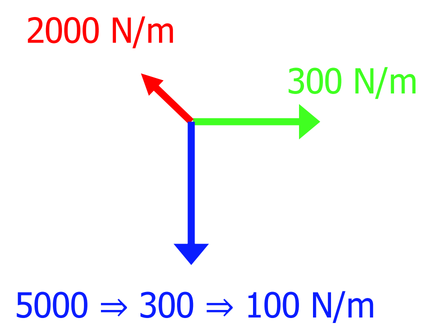
Programming robot motion

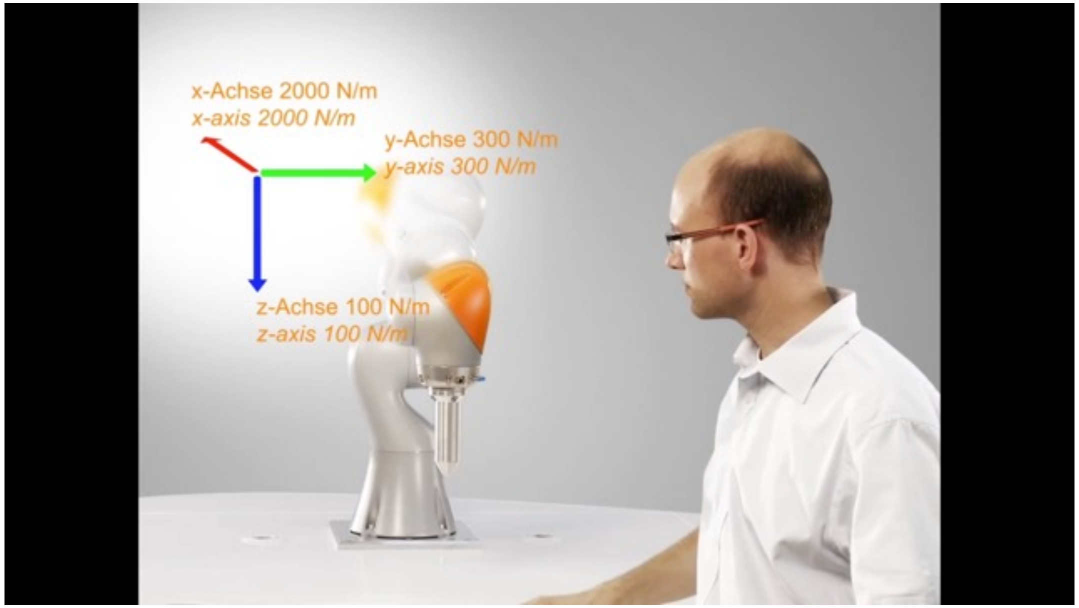
Executing nominal trajectories and “complying” with uncertainties

video

Programming robot compliance

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





video

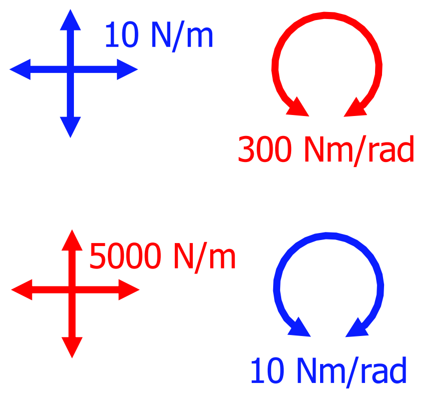
$$\Delta p \rightarrow F = K\,\Delta p$$

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

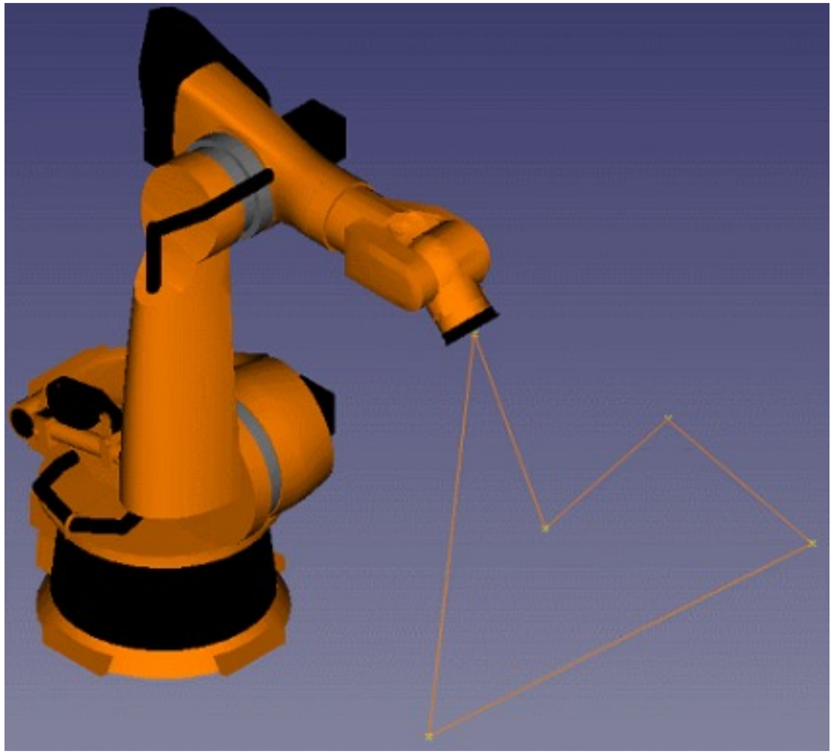
the working industrial solution

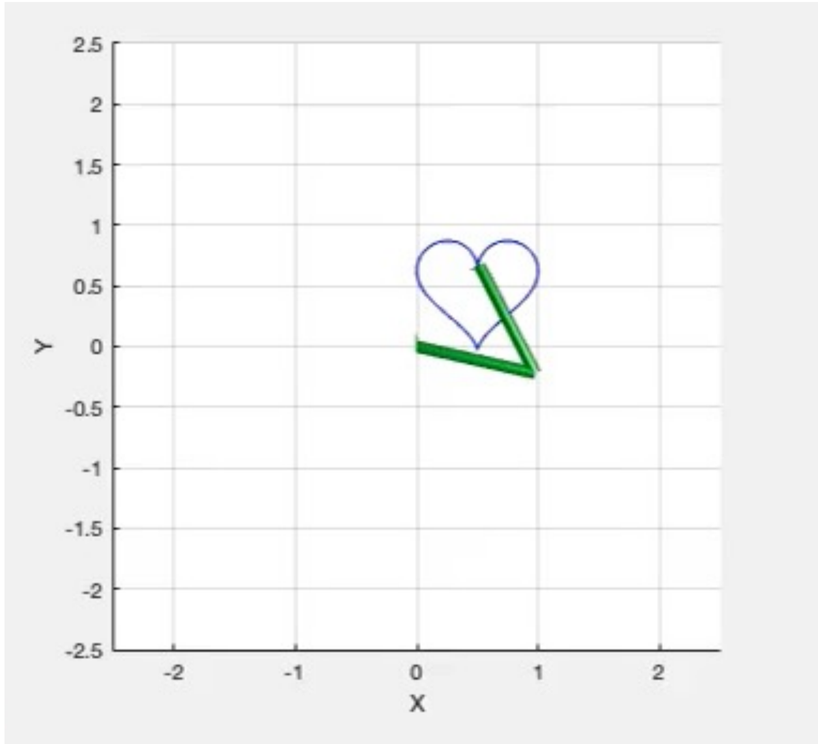
more videos on
KUKA Robotics YouTube Channel

Program

- Introduction
  - Manipulator arms (+ some on a mobile base)
  - Industrial and service applications
- Components
  - Mechanical structures
  - Actuators and transmissions
  - Sensors
    - proprioceptive (encoder, tacho)
    - exteroceptive (force/torque, depth, vision, infrared, ultrasound, laser)
- Kinematic models
  - Minimal representations of orientation
  - 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

Planning Cartesian trajectories





video

KUKA 6R articulated robot

2R planar robot

```
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;
```

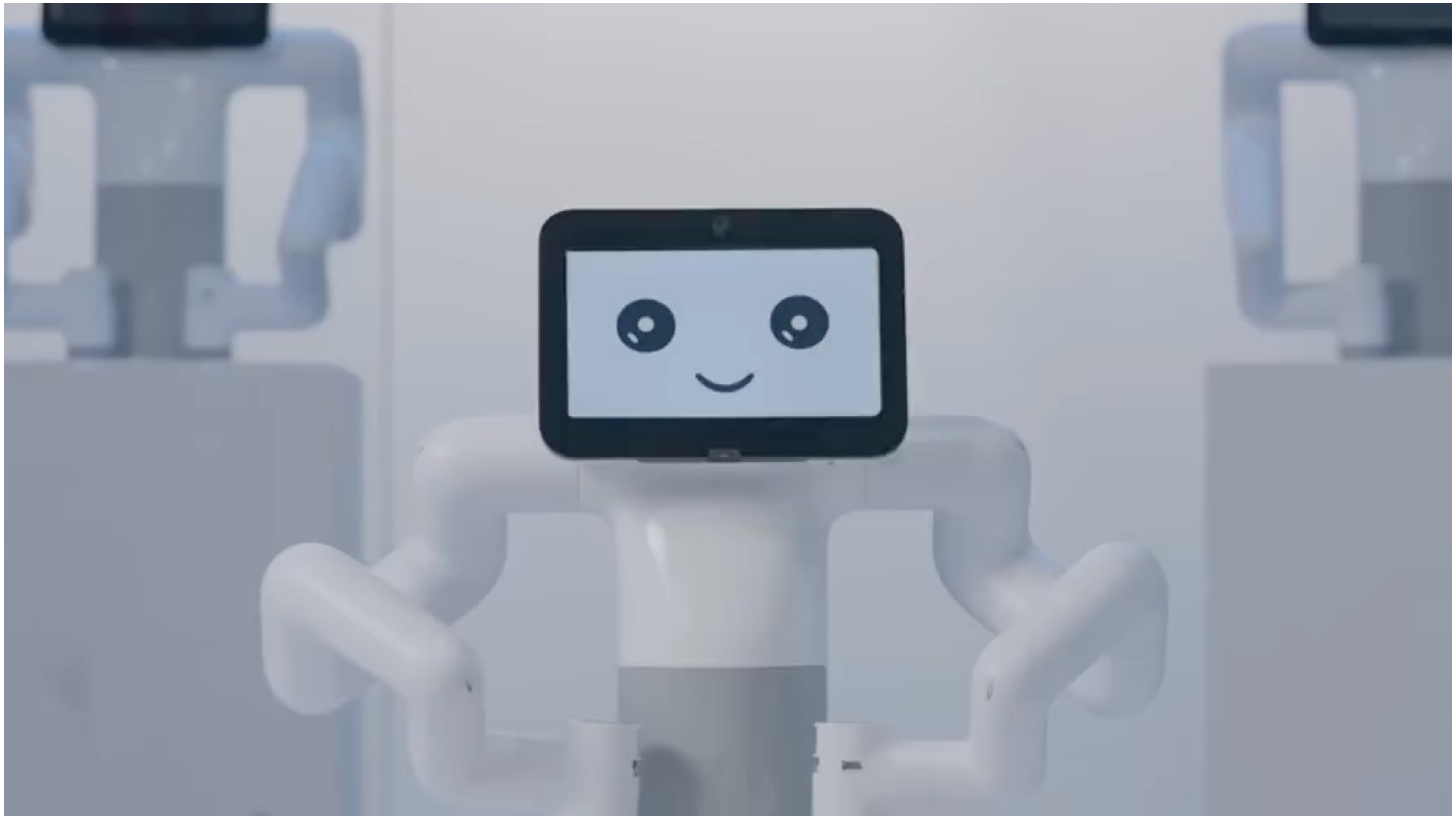
MATLAB code (Diaco & Ficorilli, Sep 2021)

Program (continued)

- Planning of motion trajectories
  - Trajectory planning in the joint space for robot manipulators
  - Trajectory planning in the 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)
  - Use of Matlab/Simulink (with Robotics Toolbox) or CoppeliaSim (V-REP)

Programming motion and behavior

video



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

Robot manipulators
available at DIAG Robotics Lab (S-218)

video

video

KUKA KR-5

KUKA LWR4+ (lightweight, about 14 kg)

Robot manipulators
available at DIAG Robotics Lab (S-218)

commercial video

upon arrival (July 2016)

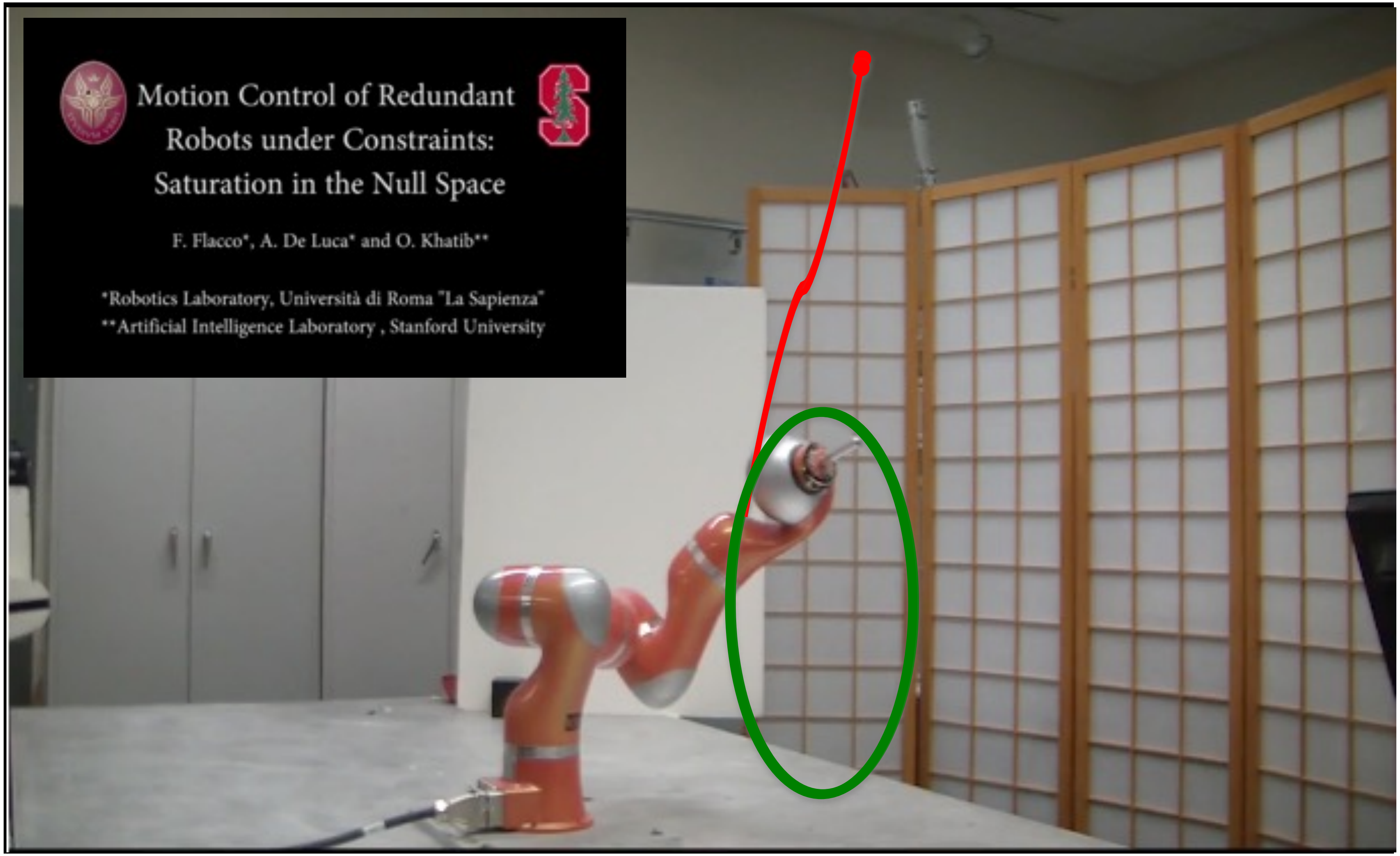
Universal Robots UR-10 (= 10 kg of payload)

I-RIM conference 2023

Fiera di Roma, 20-22 October 2023

- 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
- 5th national I-RIM conference
  - scientific presentations, workshops, expo, demos …
  - in conjunction with MakerFaire Europe
  - registration for students is very low
- Student staff needed!
  - some duties and many bonuses …
  - contact asap Prof. Marilena Vendittelli, General Chair of I-RIM 2023

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)

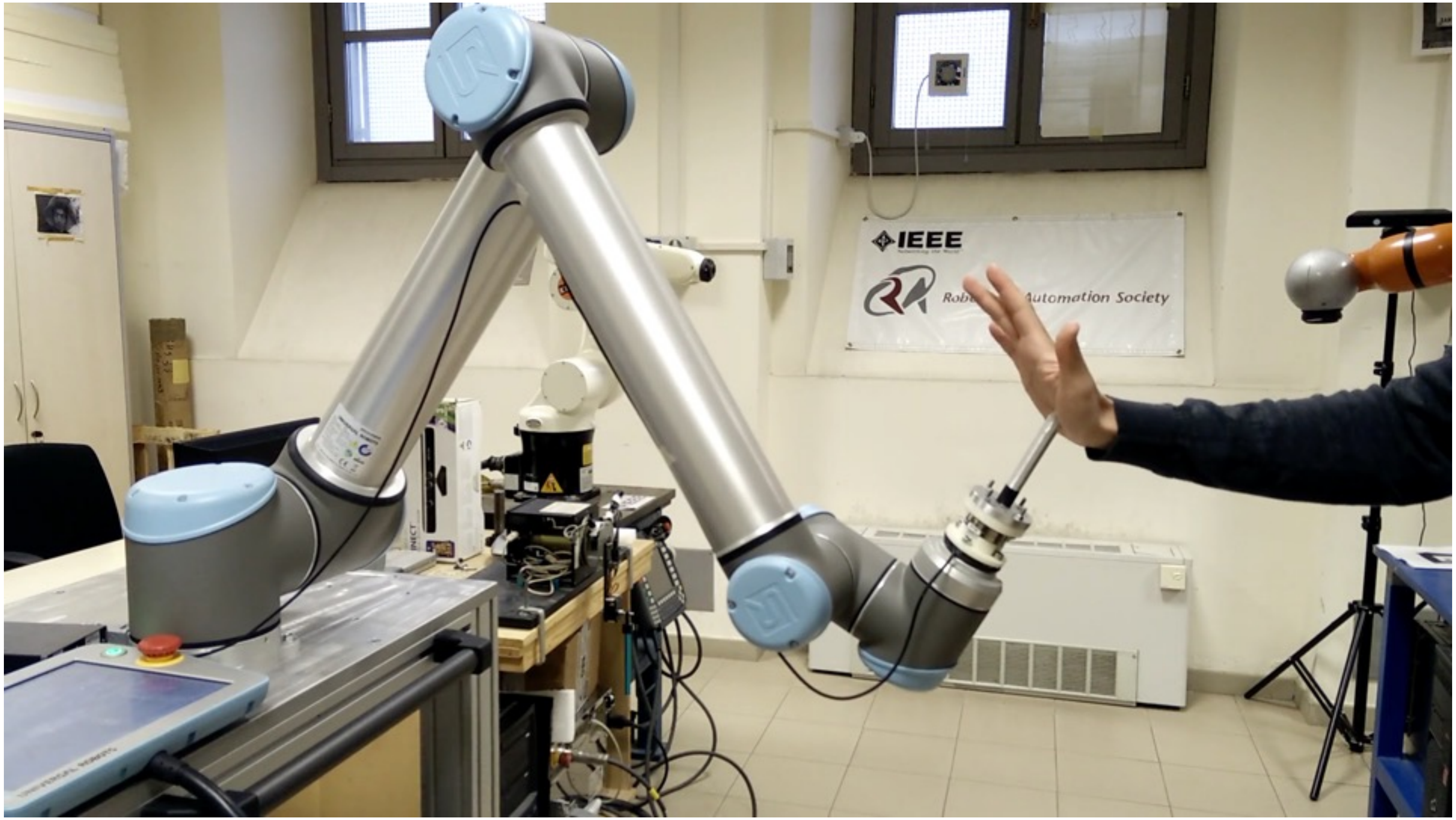
video DIAG Sapienza/Stanford, IEEE ICRA 2012

Safe physical human-robot interaction
(sensor-less (!) and on a conventional industrial robot)

video DIAG Sapienza, IEEE ICRA 2013

Human-robot collaboration

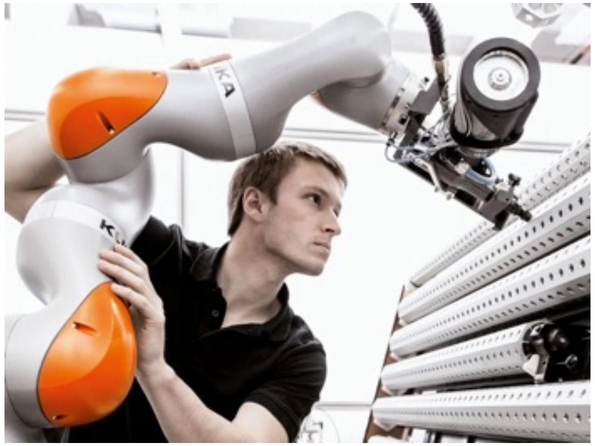
(with a real F/T and a "virtual" sensor to distinguish contacts)



video DIAG Sapienza, J. of Mechatronics, 2018

More robots …

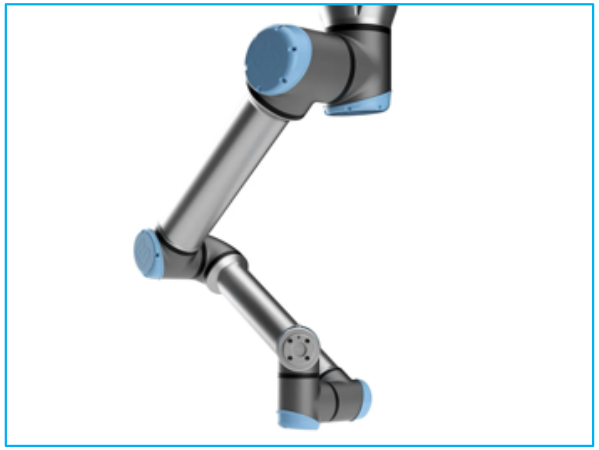
@IEEE https://robotsguide.com



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

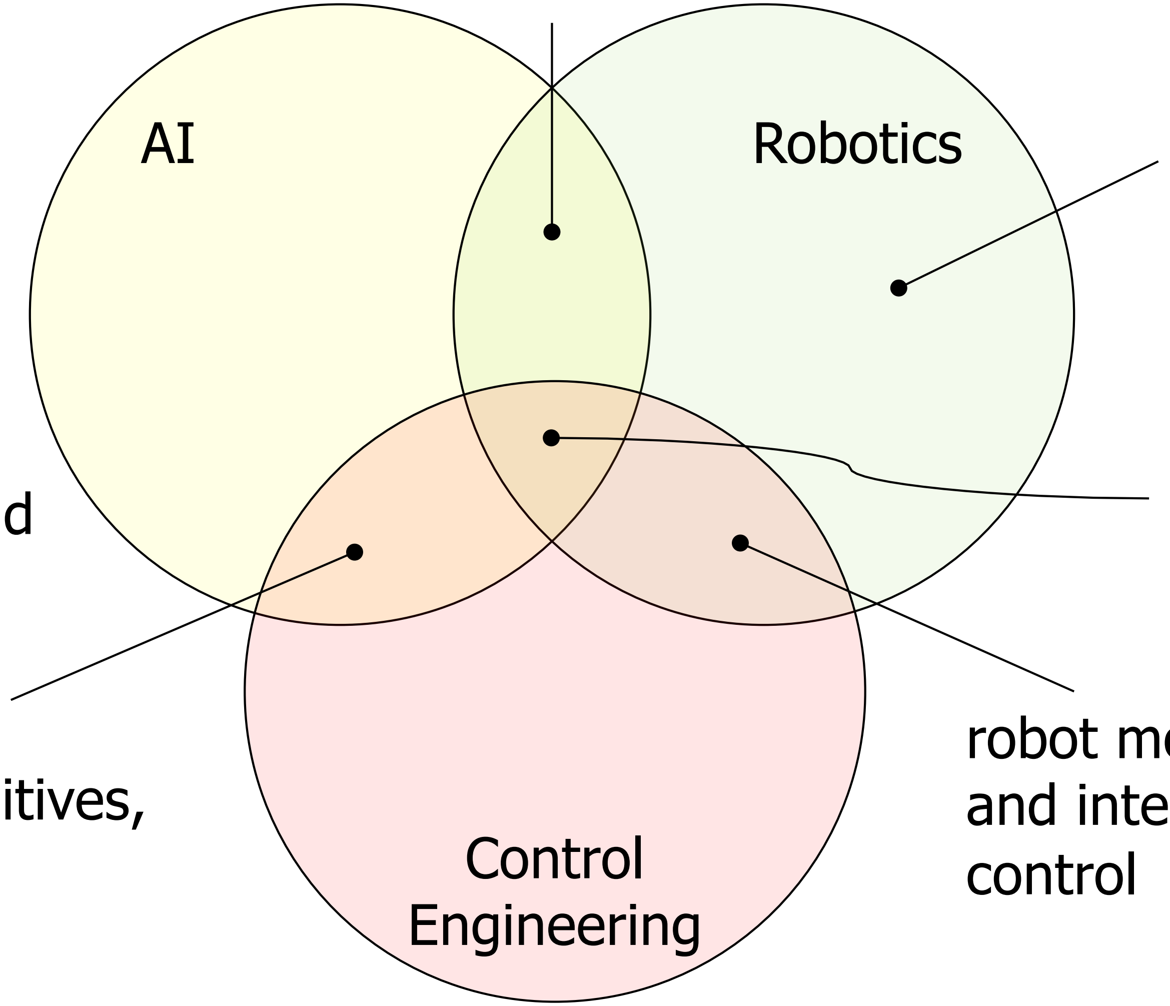
OCRobotics Explorer
snake arm
UK 2009

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



Levels of robot autonomy

in industrial applications

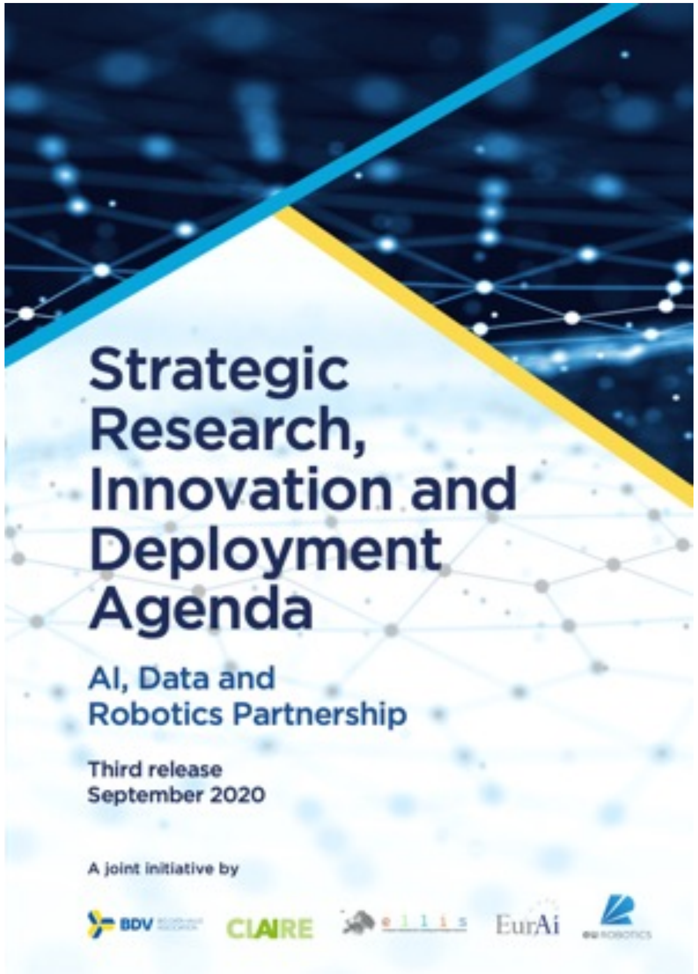
THE FIVE LEVELS OF AUTONOMY IN ROBOTS

	NO AUTONOMY, REMOTE CONTROL	NO AUTONOMY, NO SENSE AND RESPOND	NO AUTONOMY BUT SENSE AND RESPOND	AUTONOMY	ADVANCED AUTONOMY
DESCRIPTION	Robot is operated manually and remotely	Robot is not aware of its internal state or external surroundings.	Robot can sense force and motion and respond according to pre-determined parameters	Robot can sense its external environment and calculate a response	Robot can identify characteristics of its external environment
EXAMPLES	Remote-operated surgical robot	Welding robot in automotive factory	Collaborative assembly robot in manufacturing	Pick-and-place robot feeding a machine with parts from an unsorted bin	Assistant robot that responds differently to a child than an adult
SAFETY	User ensures safety	Sensors on cages	Settings for force and speed	Hard code overrides probabilistic algorithms	Hard code overrides probabilistic algorithms

NO AI DETERMINISTIC ALGORITHMS → PROBABILISTIC ALGORITHMS *HIGH AI*

source, IFR 2022

Horizon Europe (2021-27)



EU link to SRIDA AI, Data and Robotics ppp

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, ….

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

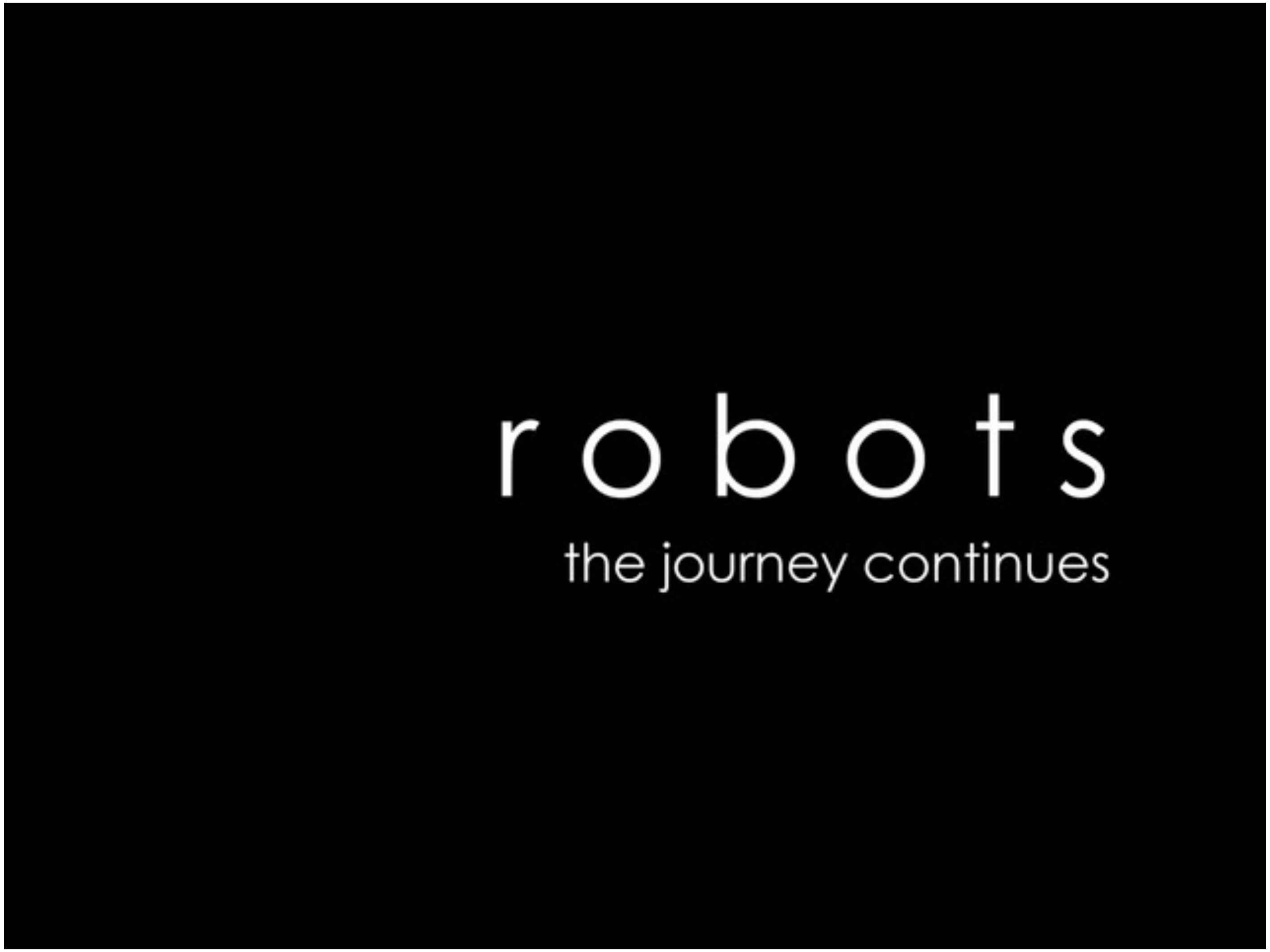
Agility (speed and strength) of collaborative robots

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)

Exams and beyond

- Type midterm test (about mid of November) + written exam
- Schedule of 2023-24 sessions
  - 2 sessions at the end of this semester
    - between January 8 and February 23, 2024
  - 2 sessions at the end of next semester
    - between June 3 and July 26, 2024
  - 1 session after the summer break
    - between September 2 and 24, 2024
  - *2 extra sessions only for students of previous years, part-time, ...*
    - *March 18–April 19 and October 9–November 6, 2024*

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

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

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 (follow link at http://www.diag.uniroma1.it/vendittelli)
- 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 Human-Robot Interaction (pHRI)
  - 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-2023-24
- 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-2023-24