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Safe control of physical human-robot interaction

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SAPIENZA
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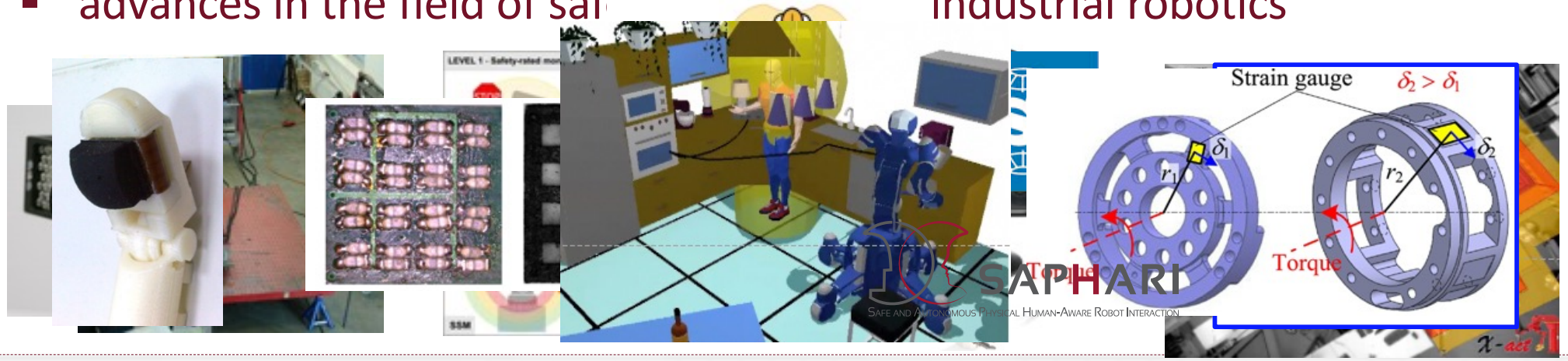
Safe physical Human-Robot Interaction (pHRI)

multiple approaches to achieve robot dependability

- mechanical design of lightweight arms
- inclusion of compliance in actuation and along the (soft) structure

  ⇒ beyond high-payload/high-precision position-controlled industrial robots
- additional exteroceptive sensors on board or in the environment
- tactile/proximity sensing and force/torque measurements
- human-oriented motion planning (`legible´ robot trajectories)
- **motion/interaction control schemes,** with safety objectives & constraints

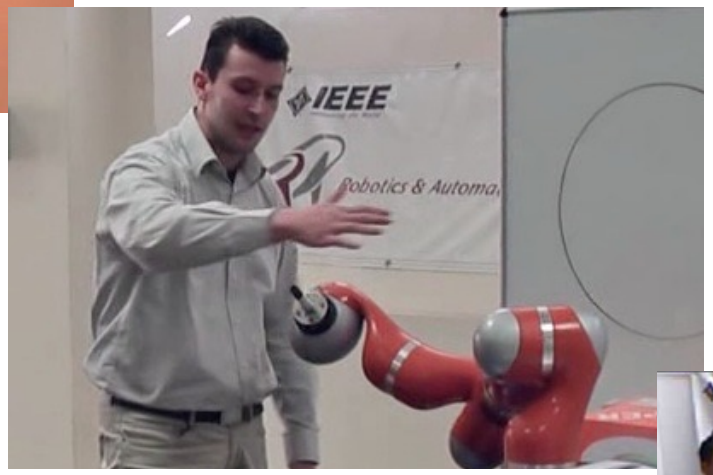
  ⇒ generating interaction plans for collaboration and coaction with humans
- advances in the field of saf[illegible] industrial robotics



Handling of collisions and intentional contacts

an architecture for **safety-related control** problems in pHRI: BioRob 2012

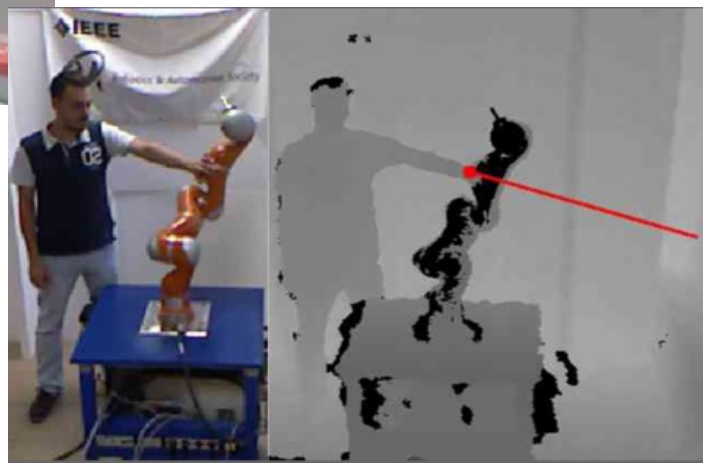
collision detection/isolation and reaction
(**without** the use of external sensing)



workspace monitoring
for **continuous**
collision avoidance
(while the task is running)

layered **control architecture**
for a consistent hierarchy
of robot behaviors

estimation and control
of intentional forces
exchanged at the contact
(**with**/**out** force sensing)

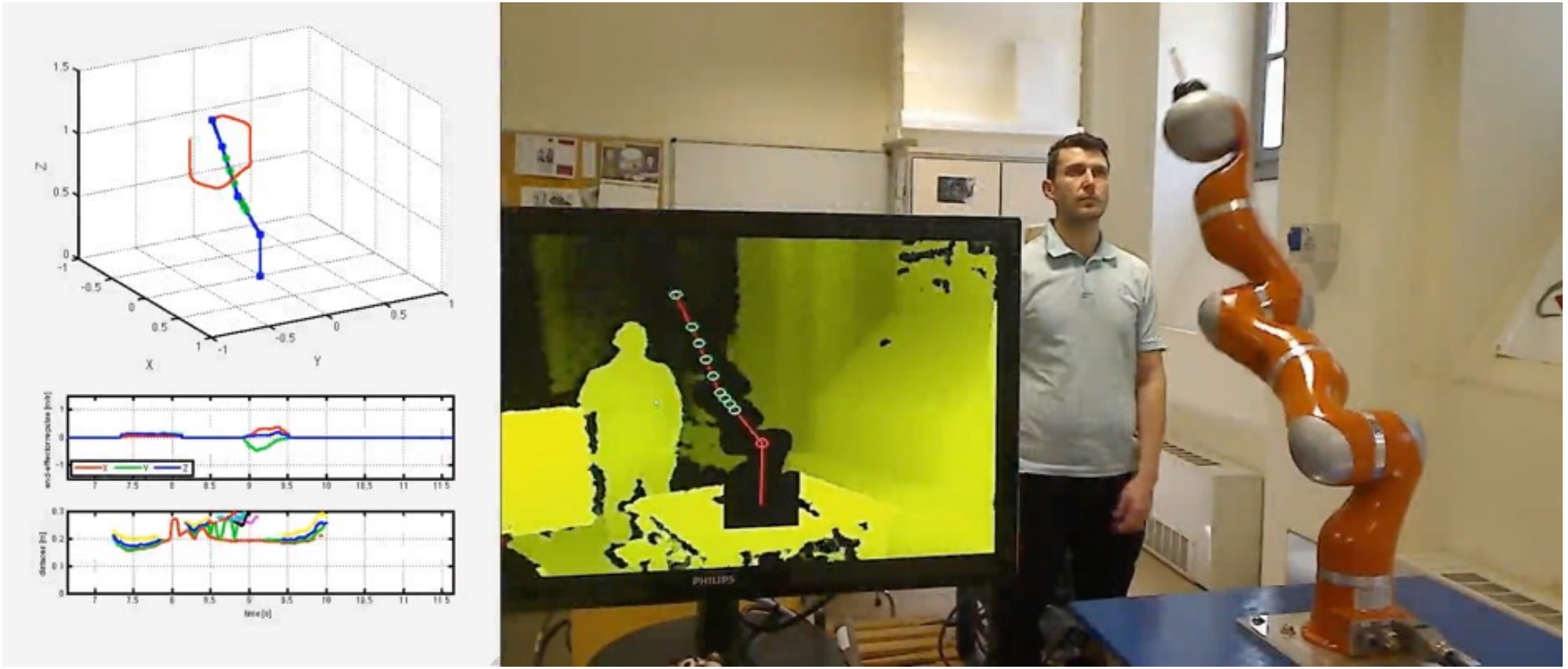


Collision avoidance and coexistence

using one (or two) **RGB-D cameras** for distance computation in 2.5D depth space

resuming a cyclic Cartesian task as soon as possible …

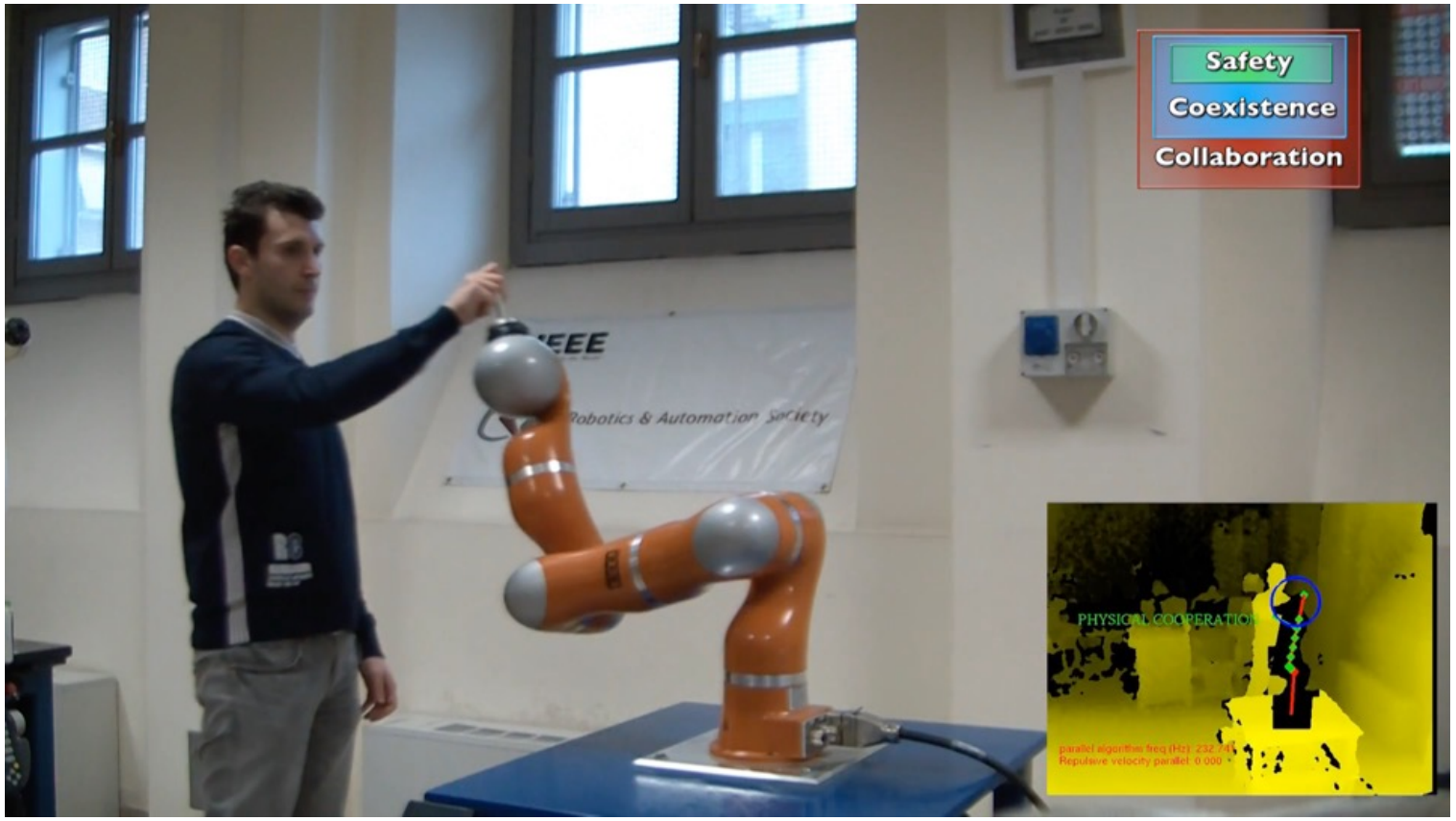
Coexistence



Kinect @30Hz, distance computations @300Hz, robot control update @1KHz

First integration of consistent robot behaviors

from coexistence to collaboration (@ DIAG): IROS 2013



Coexistence

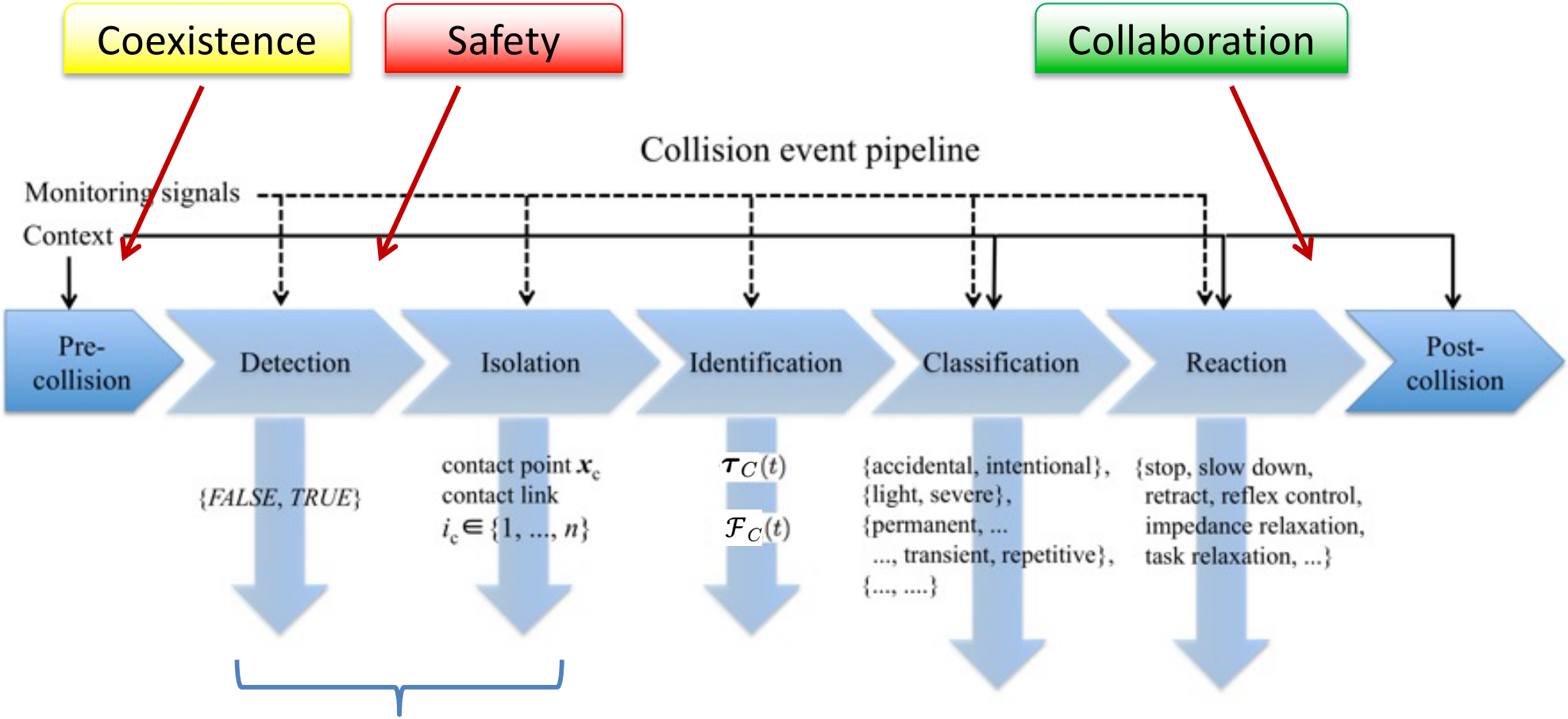
Collaboration

gesture (hand waving): target for collaboration

rapid pushing: stop collaboration

Collision event pipeline

Haddadin, De Luca, Albu-Schäffer: IEEE T-RO 2017



A. De Luca, R. Mattone: "Sensorless robot collision detection and hybrid force/motion control," *ICRA 2005*

context information is needed (or useful) to take the right or most suitable decisions

Residual signals

physical properties and useful model-based monitoring signals

robot dynamics $$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{\tau} + \boldsymbol{\tau}_C$$

total energy

$$E = T + U_g = \frac{1}{2}\dot{\boldsymbol{q}}^T \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} + U_g(\boldsymbol{q}) \quad \Longrightarrow \quad \dot{E} = \dot{\boldsymbol{q}}^T\left(\boldsymbol{\tau} + \boldsymbol{\tau}_C - \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}})\right)$$

generalized momentum

$$\boldsymbol{p} = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} \quad \Longrightarrow \quad \dot{\boldsymbol{p}} = \boldsymbol{\tau} + \boldsymbol{\tau}_C + \boldsymbol{S}^T(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}})$$

computable monitoring signals … that are sensitive to collisions

$$\sigma = k_\sigma\left(E - \int_0^t \left(\dot{\boldsymbol{q}}^T(\boldsymbol{\tau} - \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}})) + \sigma\right) ds\right) \quad \Longrightarrow \quad \dot{\sigma} = k_\sigma\left(\dot{\boldsymbol{q}}^T\boldsymbol{\tau}_C - \sigma\right)$$

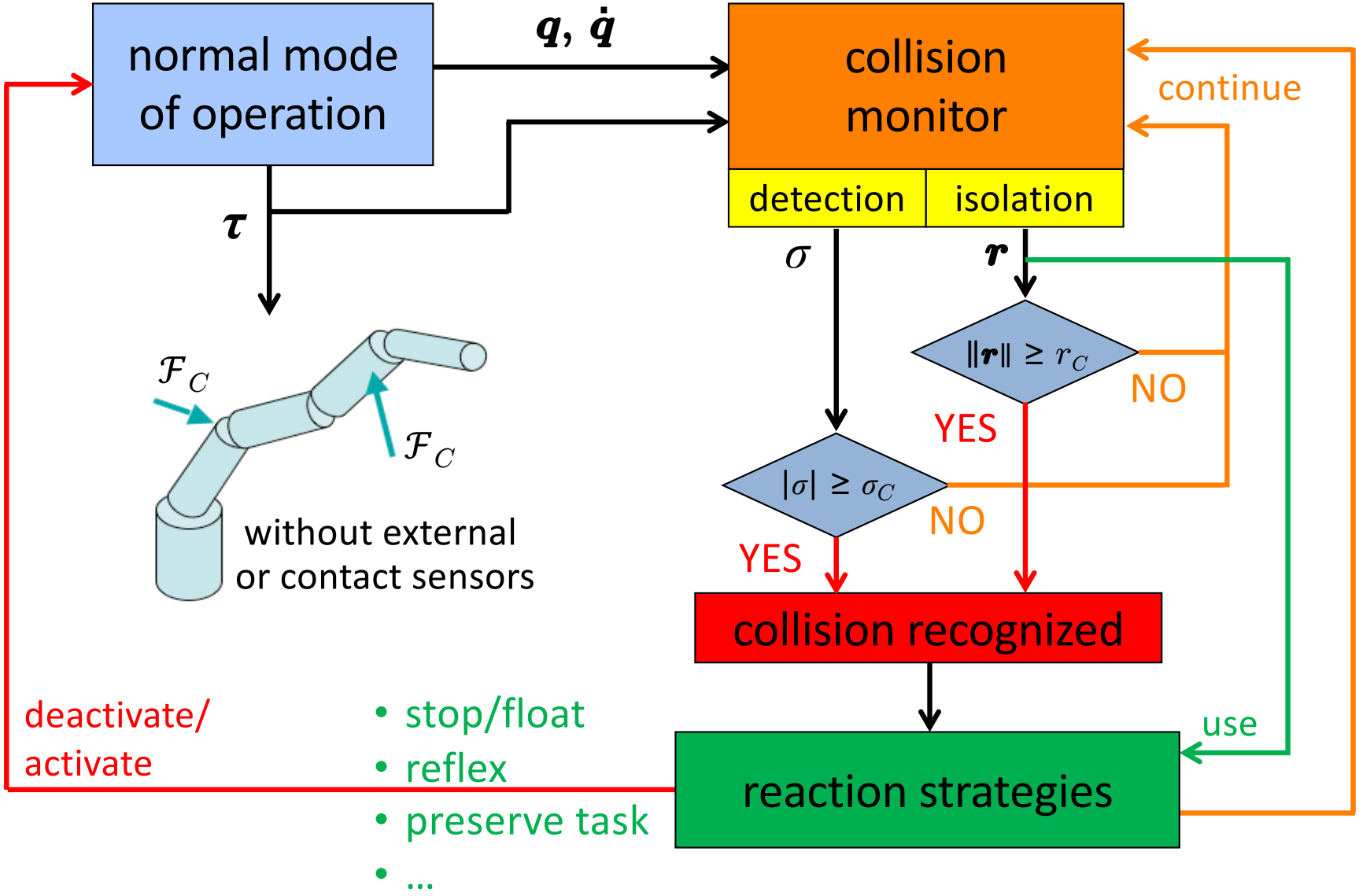
for collision detection

$$\boldsymbol{r} = \boldsymbol{K}_r\left(\boldsymbol{p} - \int_0^t \left(\boldsymbol{\tau} + \boldsymbol{S}^T(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{r}\right) ds\right)$$

for collision detection and isolation $$\Longrightarrow \quad \dot{\boldsymbol{r}} = \boldsymbol{K}_r\left(\boldsymbol{\tau}_C - \boldsymbol{r}\right)$$

Monitoring collisions without external sensing

with a portfolio of several reaction strategies



Early implementations

momentum-based collision detection and reaction (@ DLR): IROS 2006 and 2008

admittance reaction

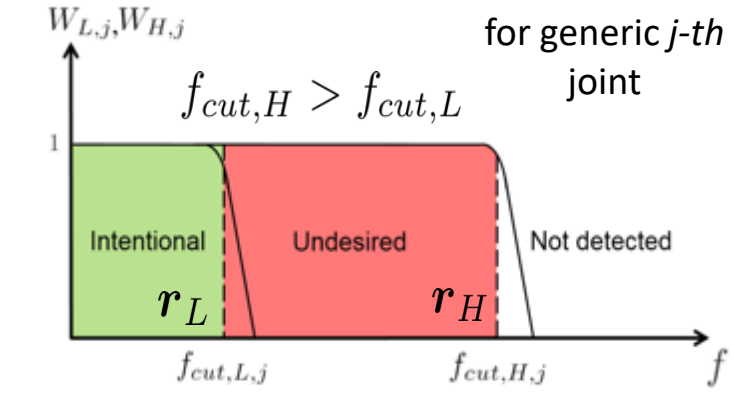
Sami, stop it!!

reflex reaction

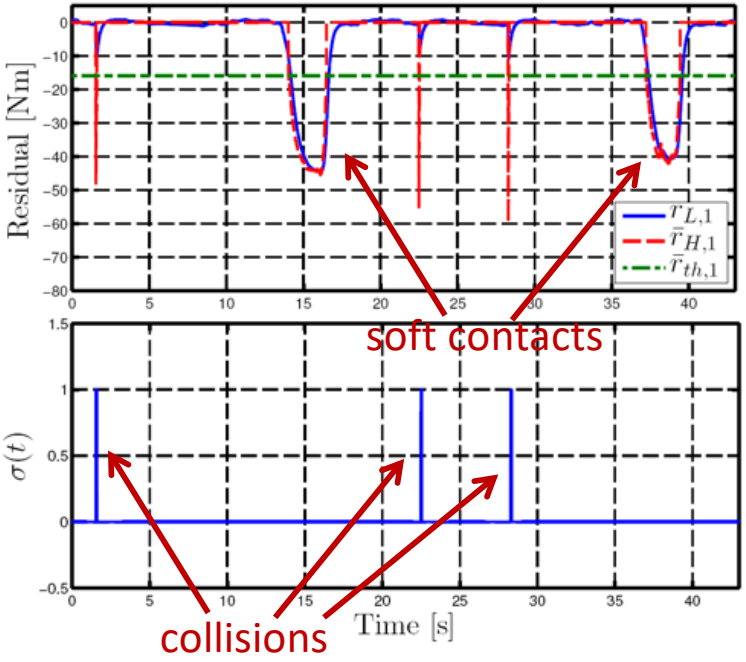
trajectory scaling

Distinguishing collisions and intentional contacts

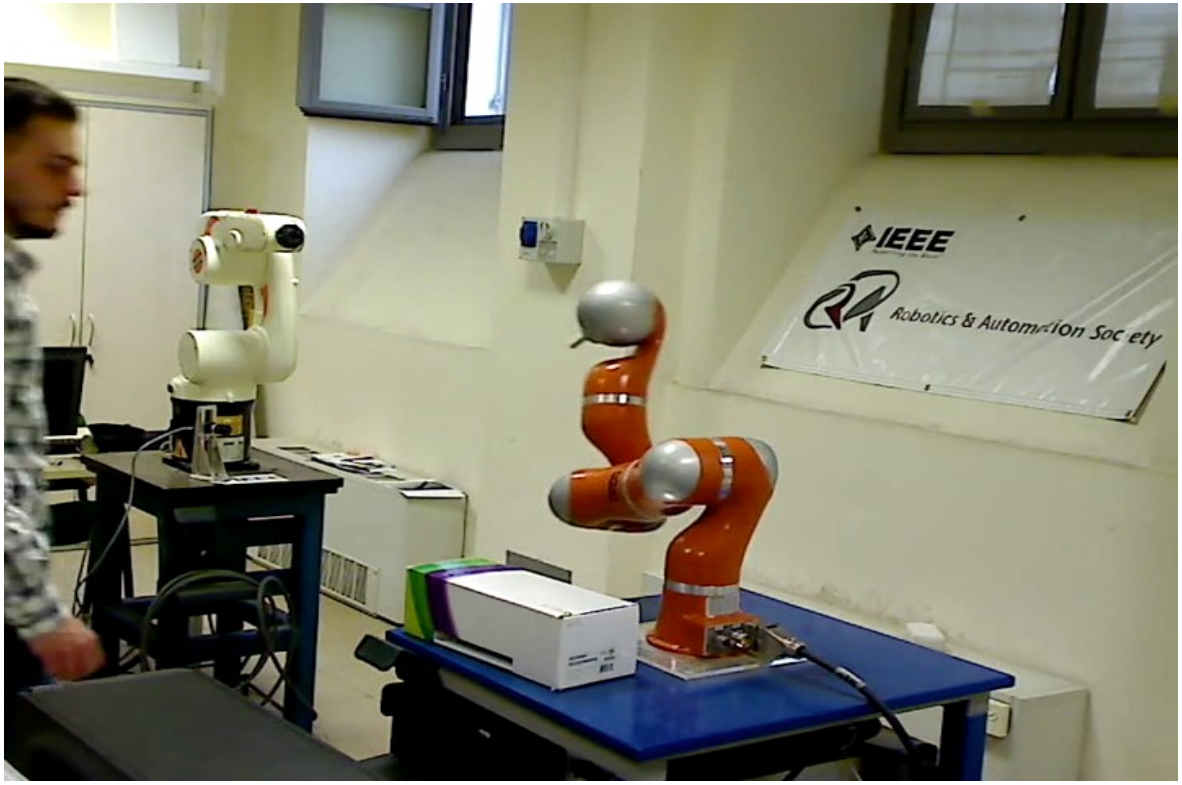
using only proprioceptive **residuals** to activate a **collaborative** behavior



for generic *j-th* joint



playing with bandwidth of residual response



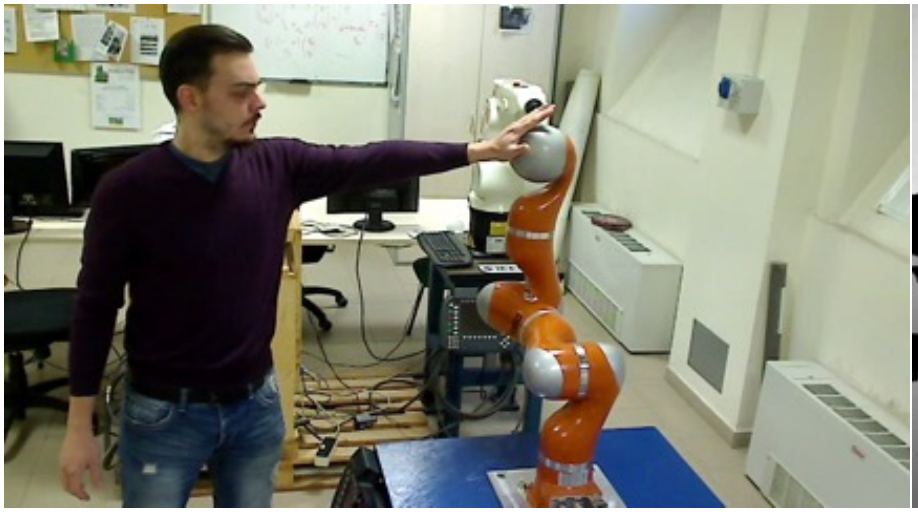
hard collision: stop and float

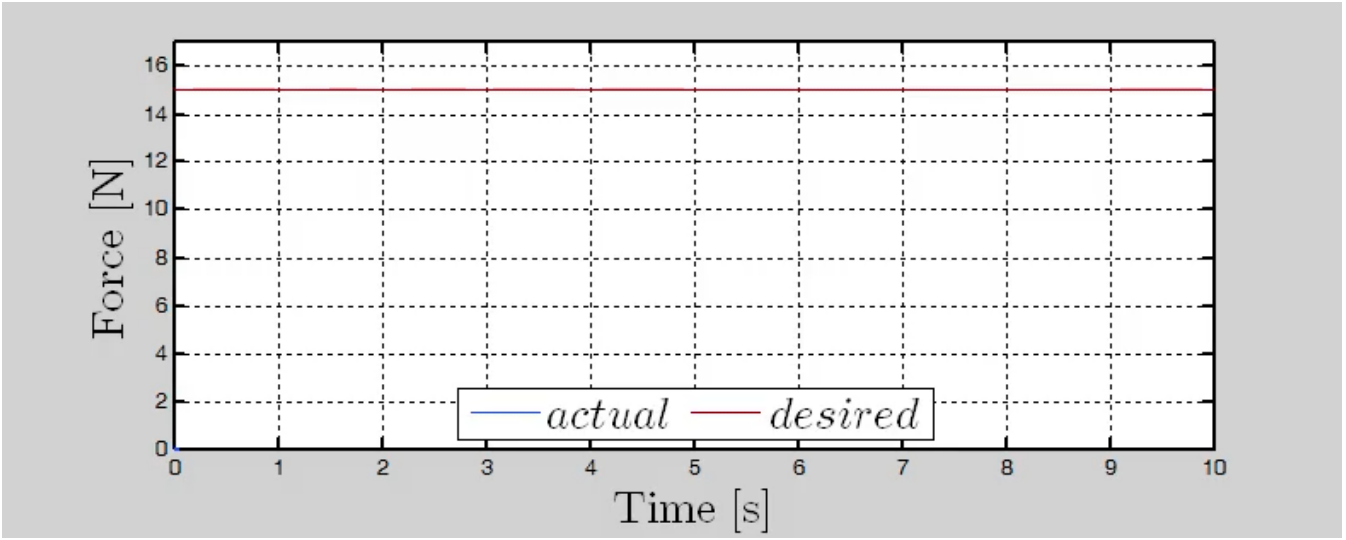
soft contact: collaborate

On-line estimation of contact force

combining proprioceptive **residual** and external **RGB-D sensor** for localization

`sensorless' contact force estimation and control (anywhere/anytime)

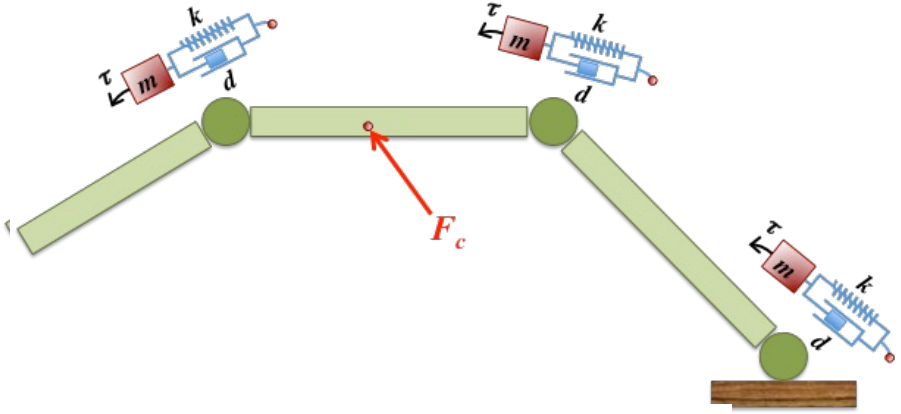




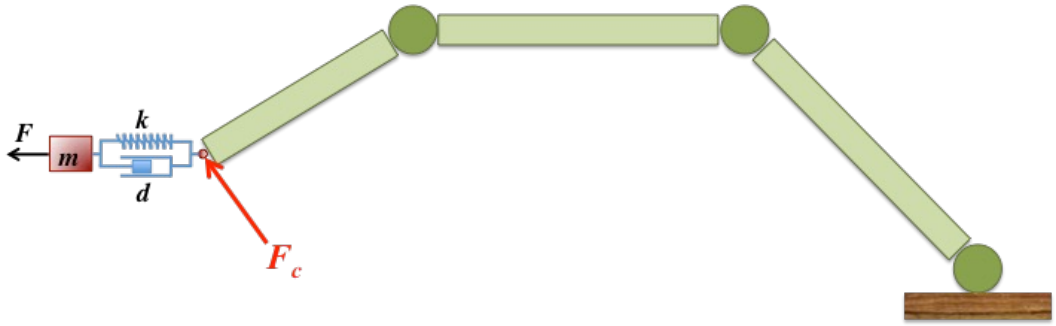
Impedance-based control of interaction

reaction to **estimated** contact forces by generalized impedance — at **different** levels

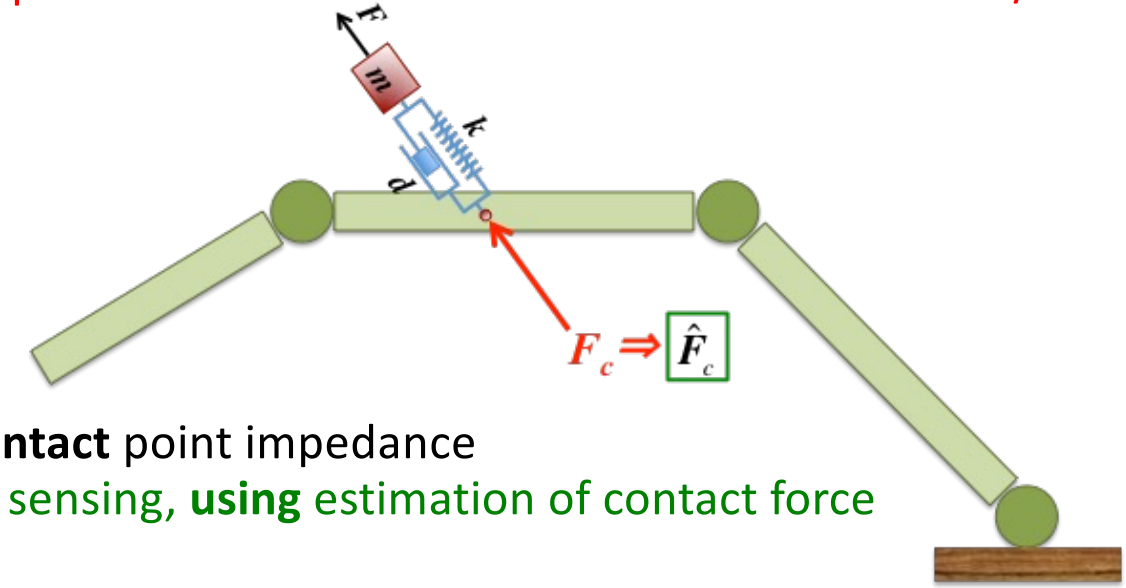
for a fully rigid robot



Joint impedance
needs joint torque sensors



Cartesian impedance
needs F/T sensor

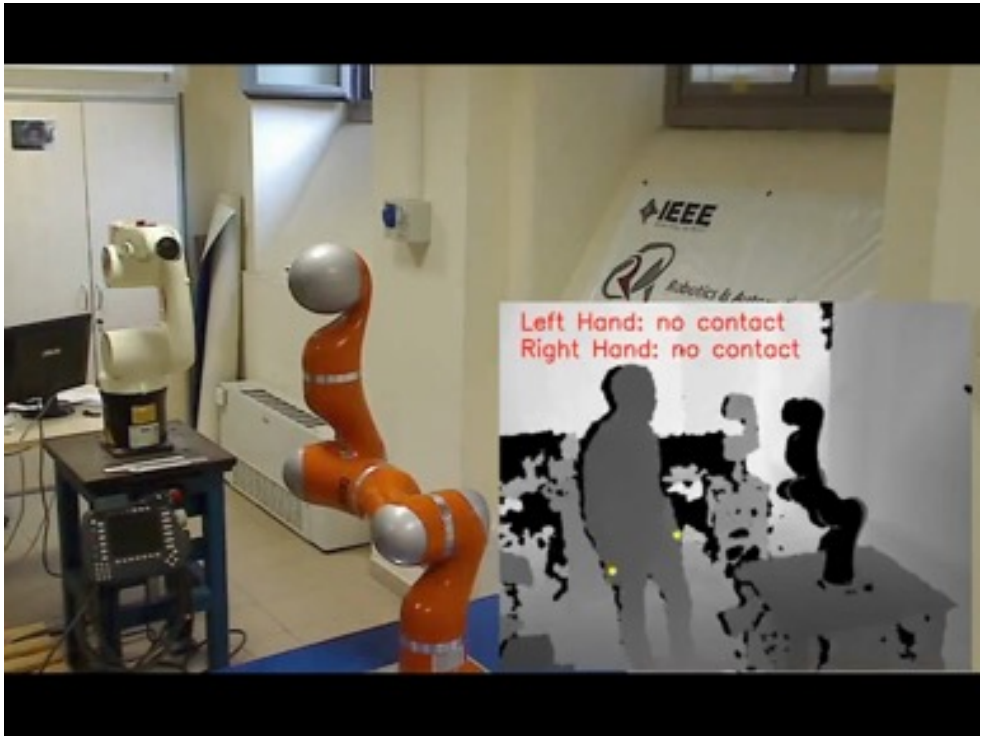


Contact point impedance
without force/torque sensing, **using** estimation of contact force

Collaboration at the contact level

admittance control and impedance control: IROS 2014, ICRA 2015

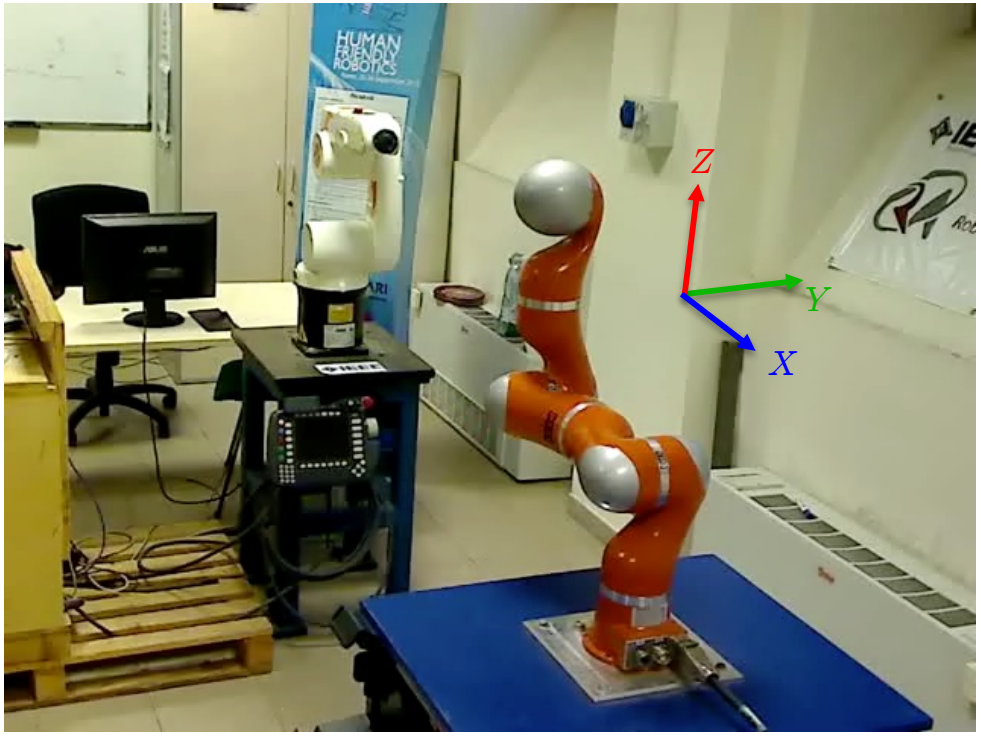
admittance control at the contact
with velocity along estimated force direction



$$\boldsymbol{r} \cong \boldsymbol{\tau}_c = \boldsymbol{J}_c^T(\boldsymbol{q})\boldsymbol{f}_c$$

$$\Longrightarrow \hat{\boldsymbol{f}}_c = \left(\boldsymbol{J}_c^T(\boldsymbol{q})\right)_W^{\#} \boldsymbol{r}$$

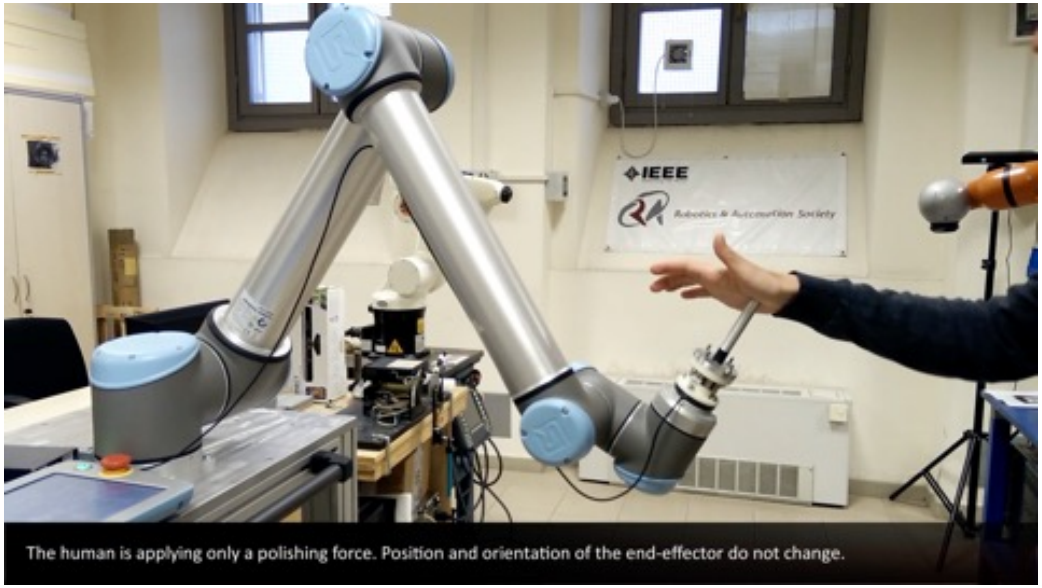
impedance control at the contact
with different apparent masses along X, Y, Z



$M_{d,X} = 20$, $M_{d,Y} = 3$, $M_{\mathrm{d},Z} = 10$ [kg]

Shaping robot reaction in various pHRI tasks

on a velocity-controlled UR10 robot and on a torque-controlled KUKA LWR4



combine residuals and F/T sensor
to discriminate contacts

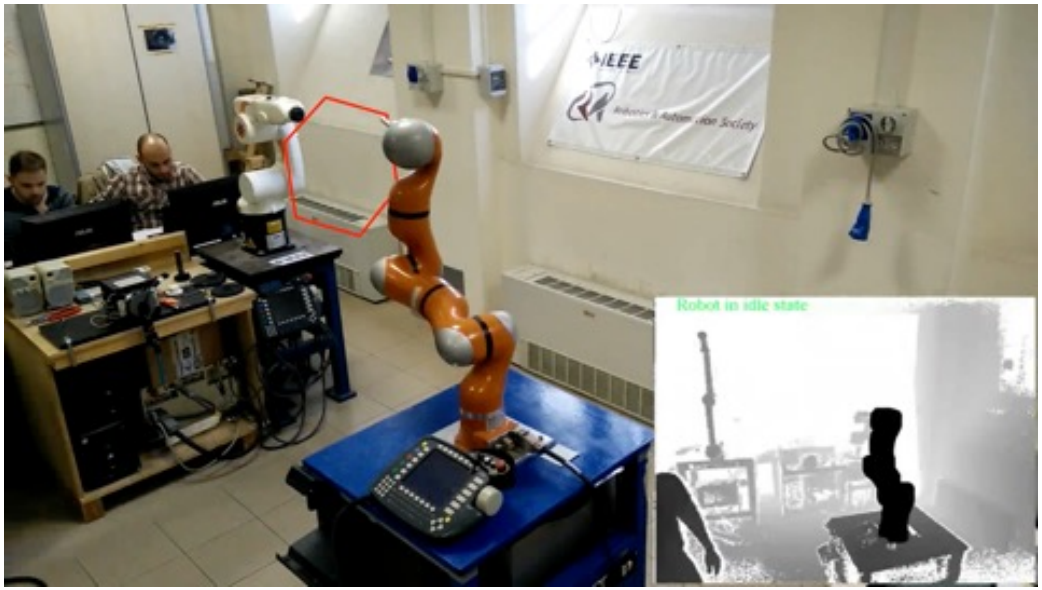
(mimic) manual polishing
while reorienting the end-effector
by kinesthetic commands

IROS 2017

Mechatronics 2018

exploit redundancy
to preserve the task
(playing with thresholds)

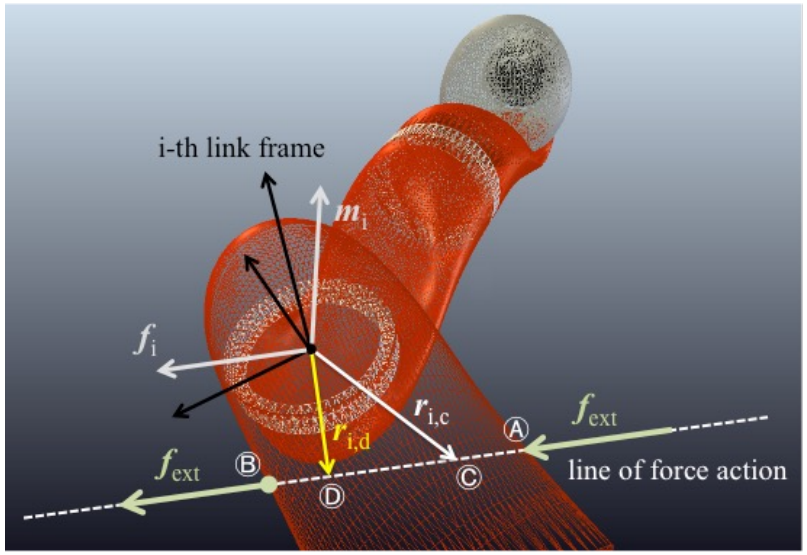
idle ⇔ relax ⇔ abort



Localization and estimation of contact force

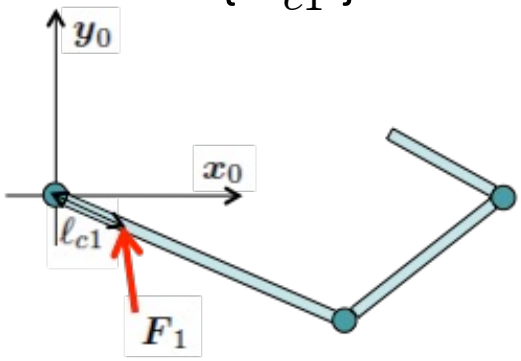
on **distal** robot limbs, even **without** external sensing

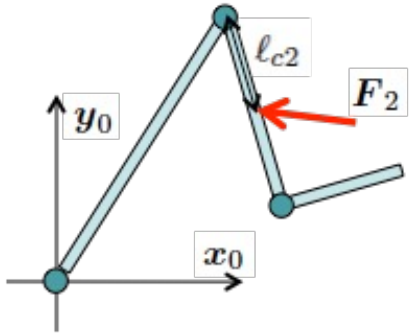
- if contact is sufficiently “down” along the kinematic chain (**≥ 6 residuals** available), estimation of **pure contact forces** needs no external information
- estimation and localization of a force on a simple 3R planar case, with contact on different links, in **static** conditions



only **normal** force to link,
if contact point is known

rank { J_{c1} } = 1

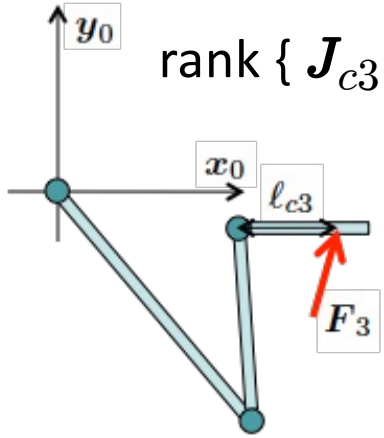




rank { J_{c2} } = 2

full force on link,
if contact point is known

full force on link,
without knowing contact

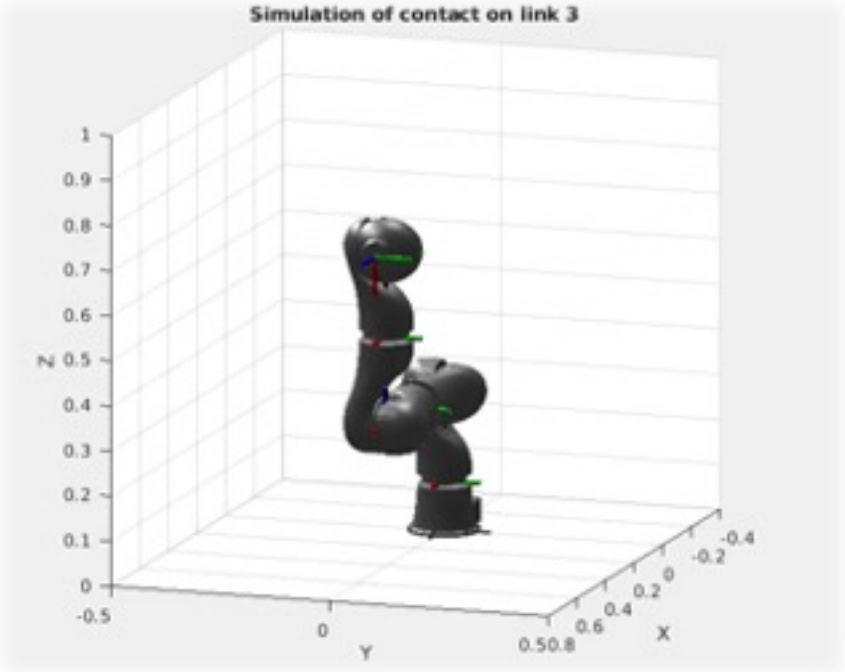


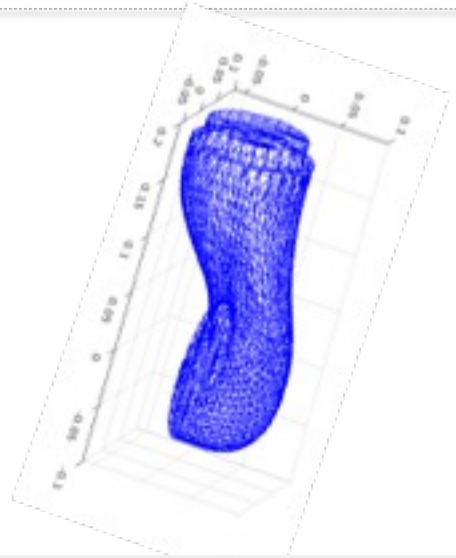
rank { J_{c3} } = 2

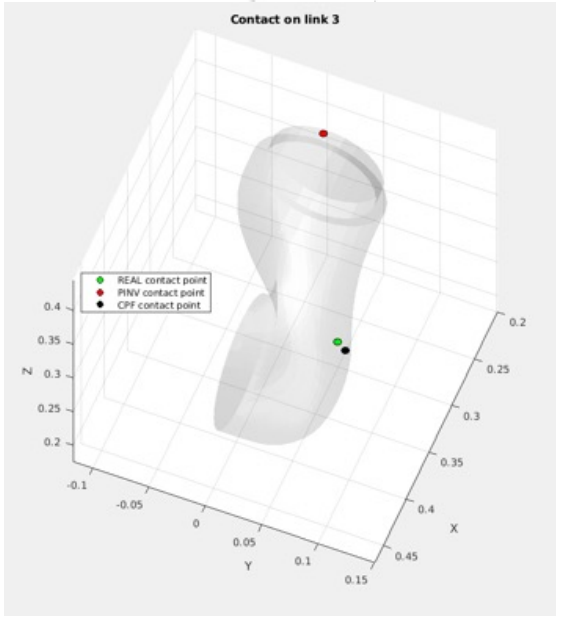
Localization and estimation of contact force

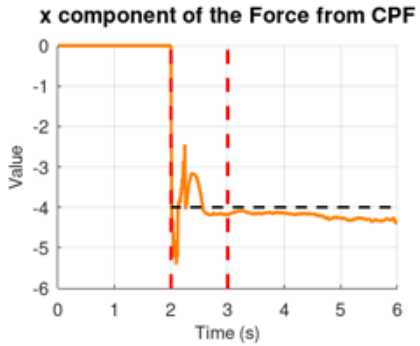
on **proximal** robot limbs, combining **residuals** and **contact particle filters (CPF)**

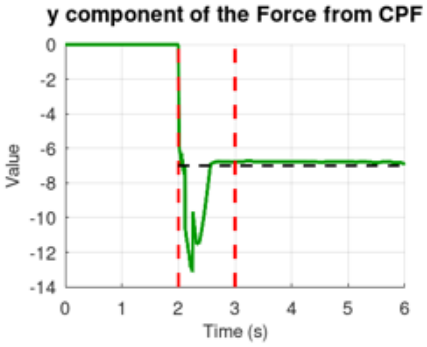
data-driven, in **dynamic** conditions

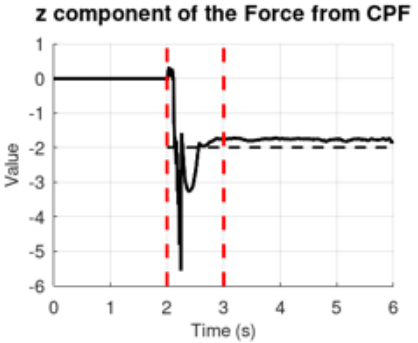


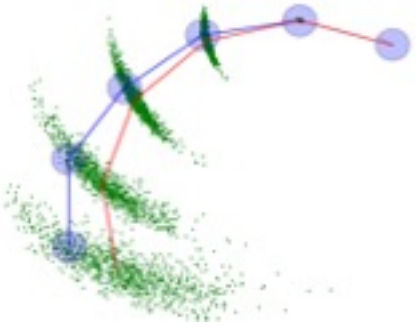






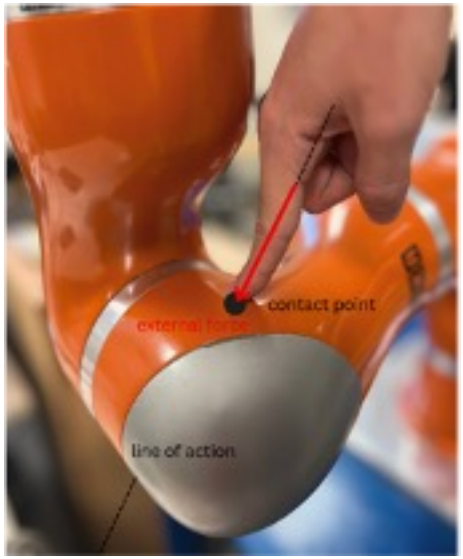


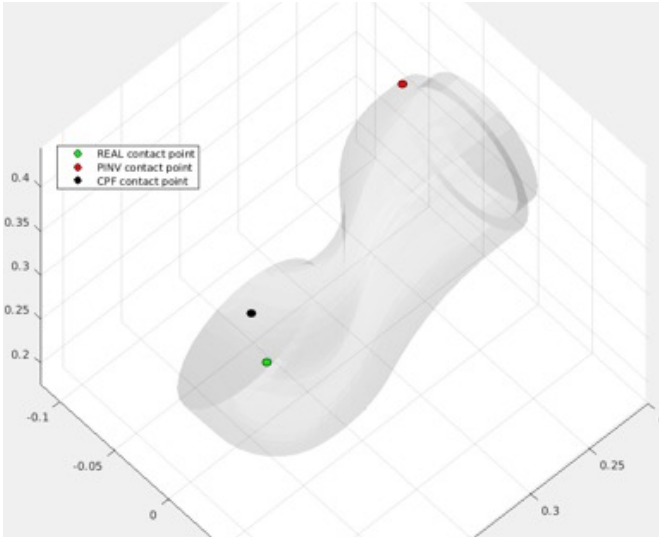


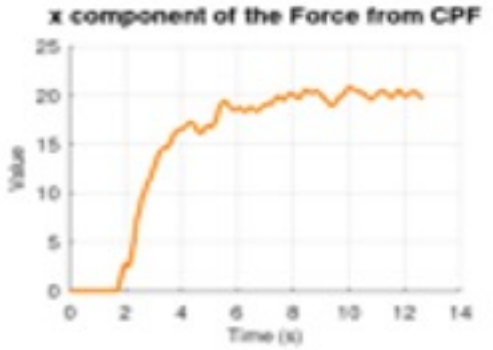


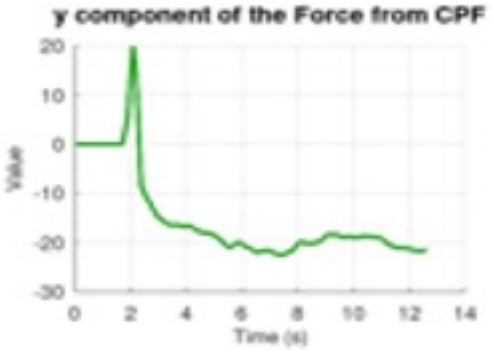
Localization and estimation of contact force

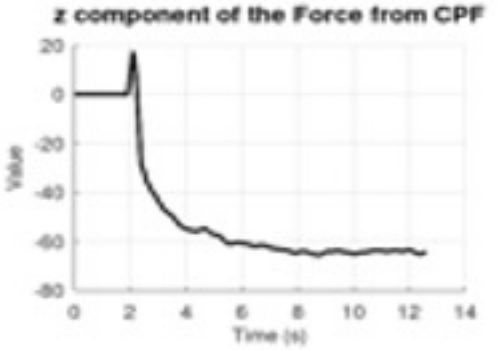
experiments with contact on link 3 of a KUKA LWR4







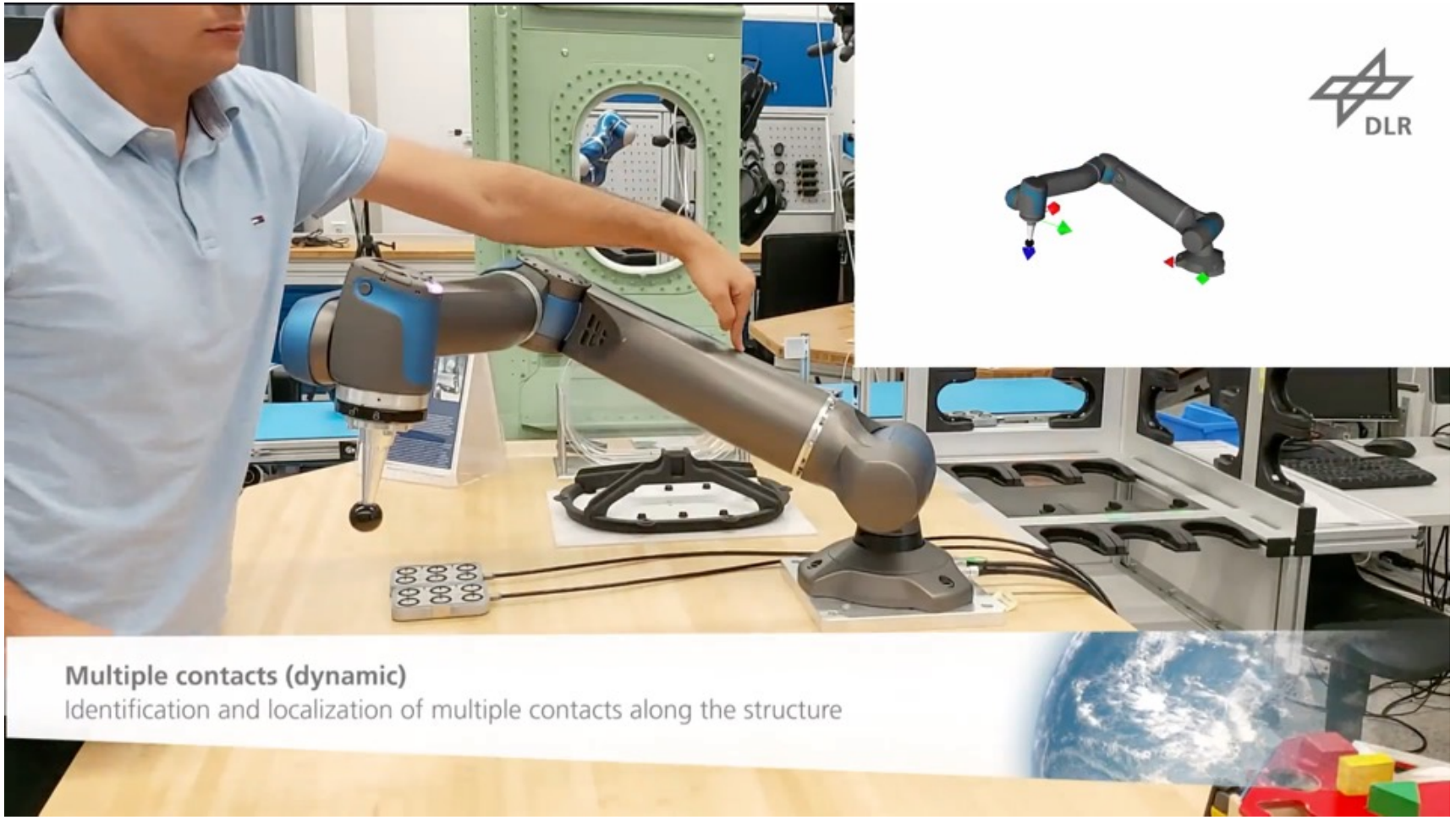




Sensing redundancy in DLR SARA robot

contact localization & force estimation, handling singularities, multiple contacts

more sensors — F/T at the wrist, Joint Torque sensors, F/T at the base: ICRA 2021



Summary

safe pHRI in the past 15+ years and in a near future

- so far …
  - physically motivated, possibly ‘sensorless’ methods for contact detection and isolation, force estimation, and interaction control
  - applied to rigid robots, with elastic joints/VSA (with/without torque sensing), flexible link & soft manipulators, humanoids, UAVs, closed control architectures …
  - “bricks” to be used for controlling different collaborative tasks
- integration of data-driven and model-based methods
- recombine cognitive and physical HRI
- multi-modal communication and interaction
  - voice, LLM, gestures, visual coordination, VR/AR, …
- (context-based) human intention prediction
  - with anticipative robot actions for better efficiency and human ergonomy
- robot learning of human behavior in collaborative tasks
  - large variety of tasks to be trained, with humans in the loop