Workshop in honor of Jean-Paul Laumond

Collège de France, Paris

July 11, 2022

On the Control of Physical Human-Robot Interaction

A mini-survey of research at Sapienza in the last 15 years

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SAPIENZA
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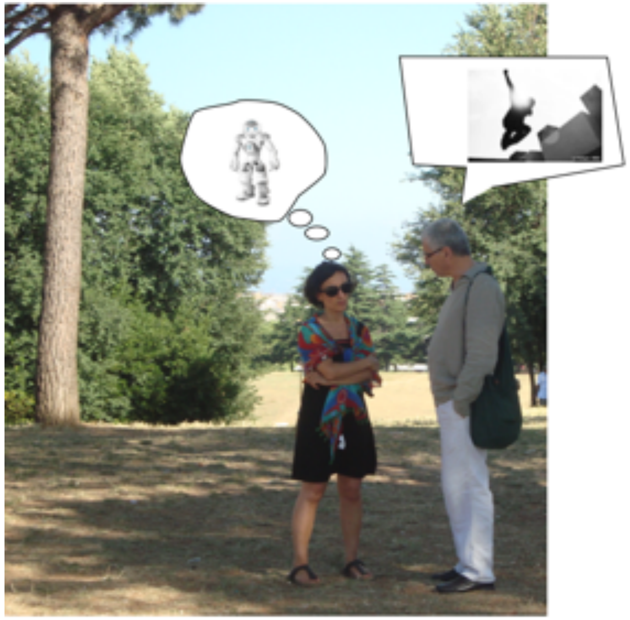
Dr. Laumond in Rome

PROMotion
final workshop
July 1995

ICRA 2016
PC meeting
January 2016

Jean-Paul in Rome

Several visits starting with 1995



Incontri al Chiostro

Robotics: Hephaistos reoffends

incontro con

Jean-Paul Laumond

venerdì 29 aprile 2011 ore 14:30
Aula Magna del Dipartimento di Informatica e Sistemistica Antonio Ruberti
via Ariosto 25, Roma

Biblioteca del Dipartimento di Informatica e Sistemistica Antonio Ruberti

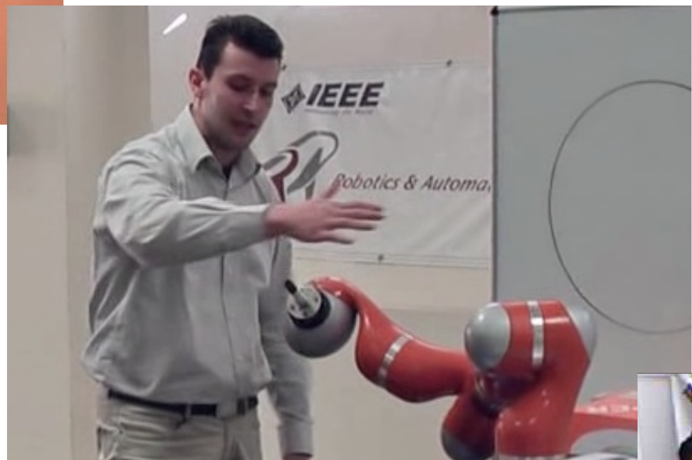
SAPIENZA UNIVERSITÀ DI ROMA

Sabbatical in 2011

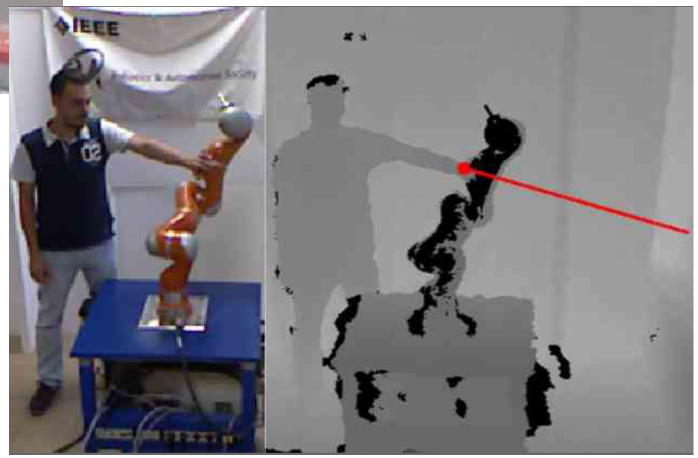
Handling of collisions and intentional contacts

Basic safety-related control problems in pHRI

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



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



estimation and control
of intentional forces
exchanged at the contact
(**without** or **with a F/T** sensor)
for human-robot collaboration

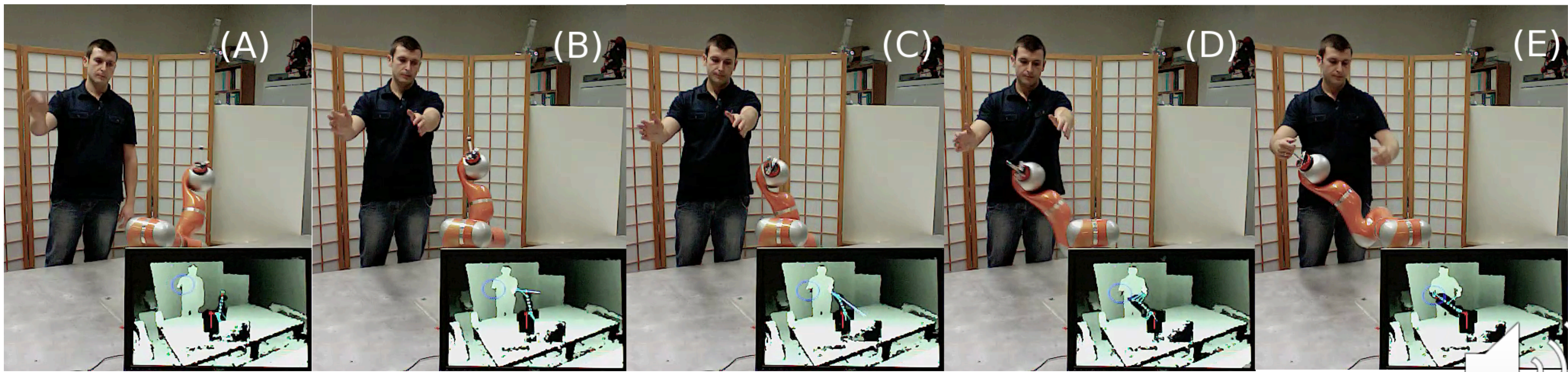
A control architecture for physical HRI

Hierarchy of consistent robot behaviors (BioRob 2012)

Safety is the most important feature of a robot that has to work close to humans (requires **collision detection and reaction**)

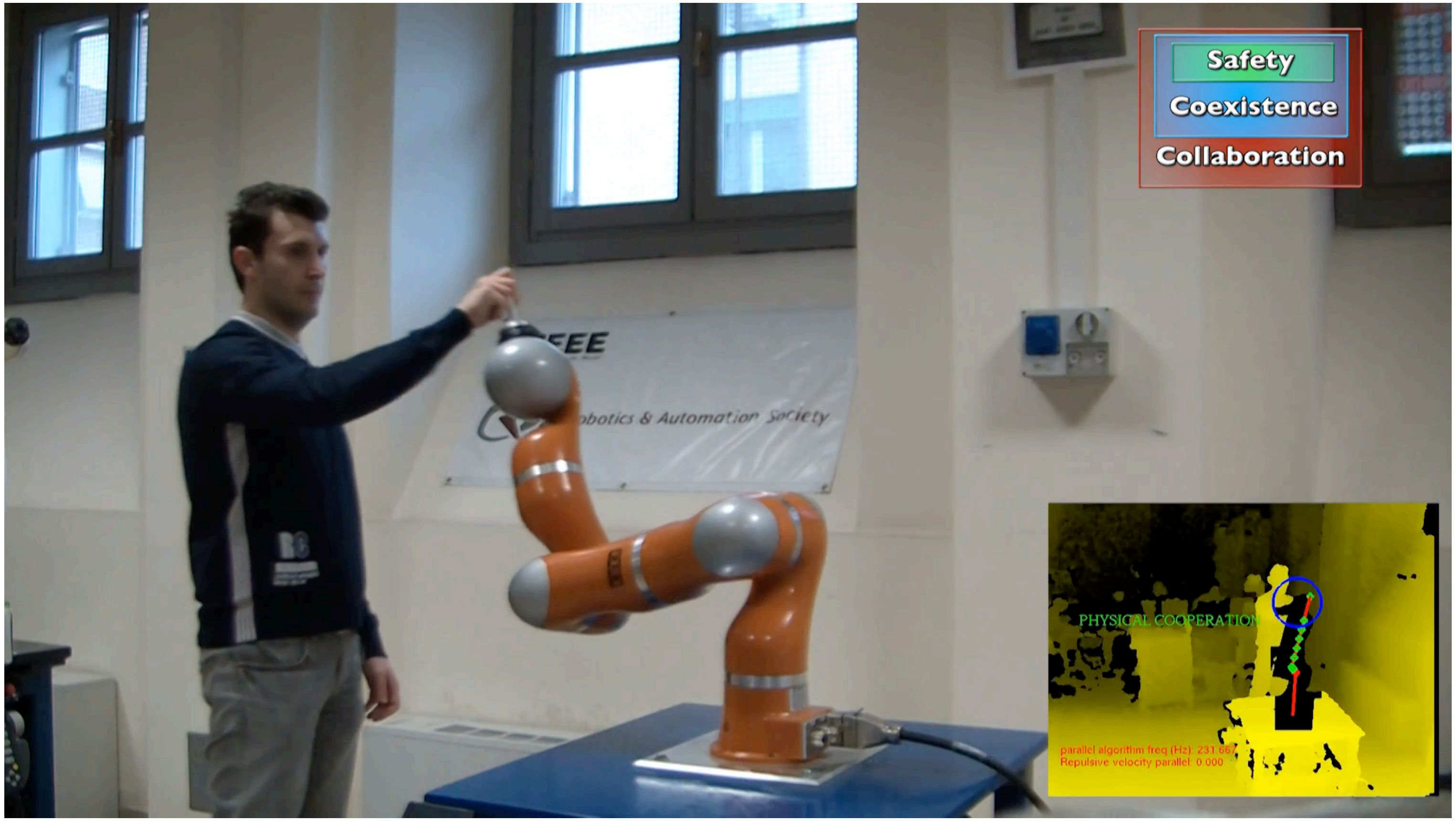
Coexistence is the robot capability of sharing the workspace with humans (**collision avoidance**)

Collaboration occurs when the robot performs complex tasks with **direct human coordination** (mostly, with **physical interaction**)



Safe coexistence and collaboration in pHRI

Excerpt from the finalist video at IROS 2013

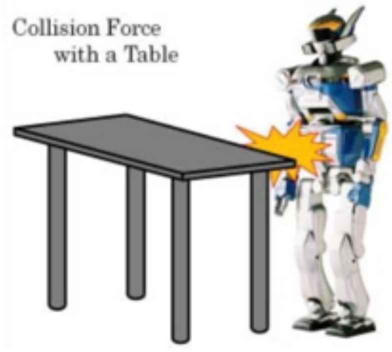


- **collaboration** through contact force identification (here, at end-effector only)

Disturbance observer to estimate contact forces in humanoids

Eiichi Yoshida, Jean-Paul Laumond *et al.* (12th IEEE Advanced Motion Control Work., 2012)

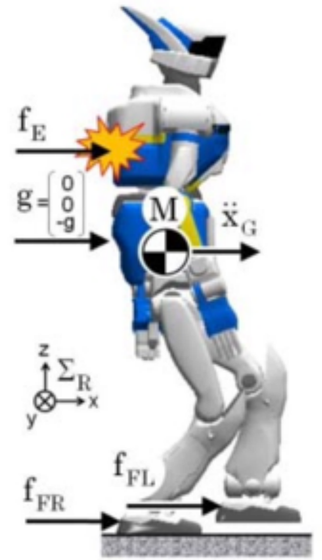
(a) Collision with human



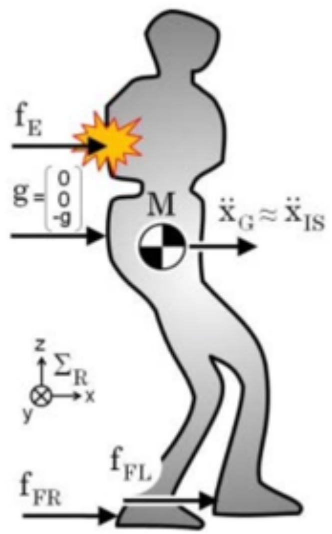
(b) Collision with the environment

(c) Force kicked by human

(d) Force pushed by human



(a) Real model



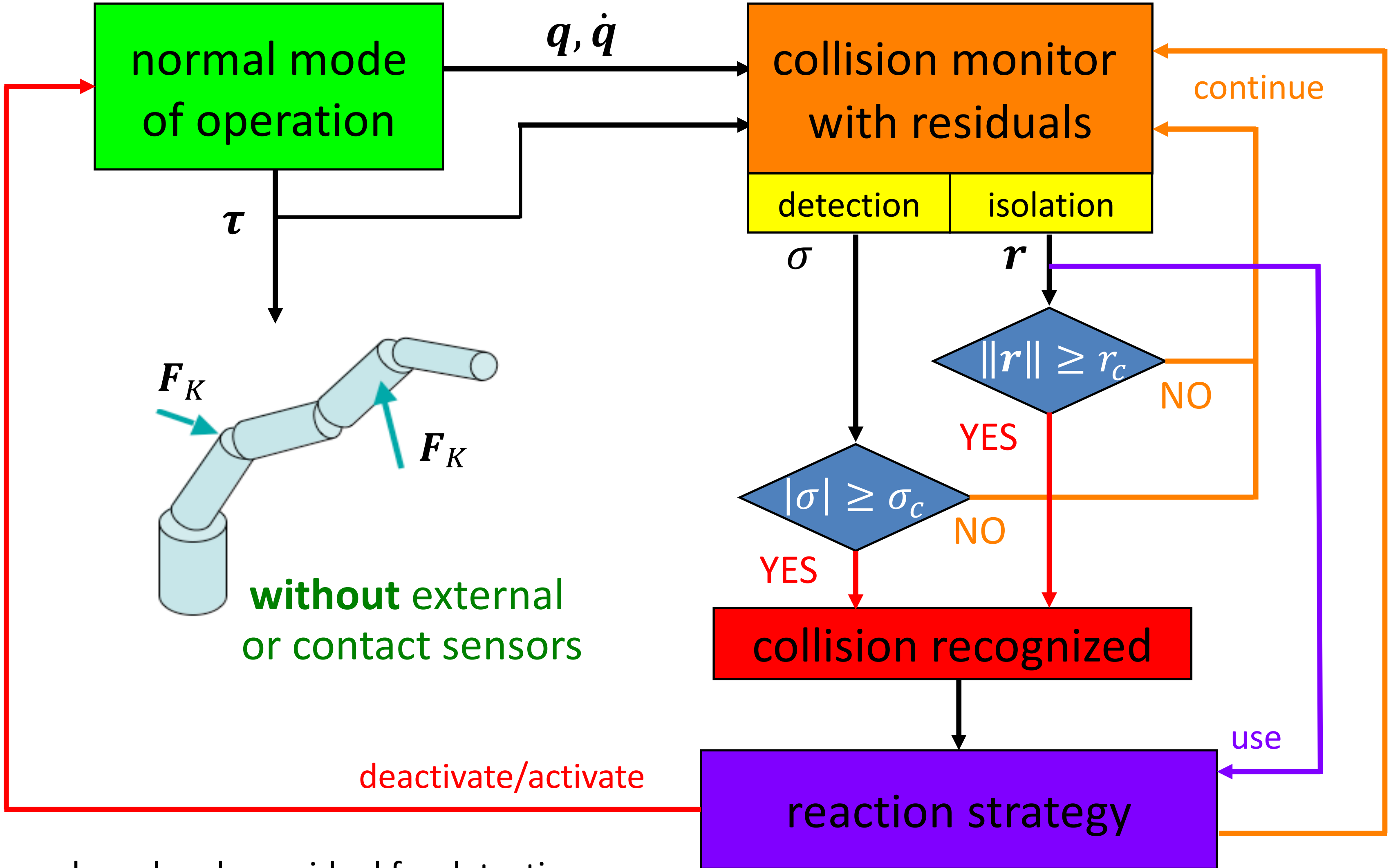
(b) Assumed model

$$M\,\ddot{x}_G = f_{FR} + f_{FL} + f_E + M\,g$$

$$f_E = M\,(\ddot{x}_G - g) - f_{FR} - f_{FL}$$

Monitoring robot collisions

Applies to **rigid and elastic** joints, **with and without** joint torque sensing (IROS 2006)

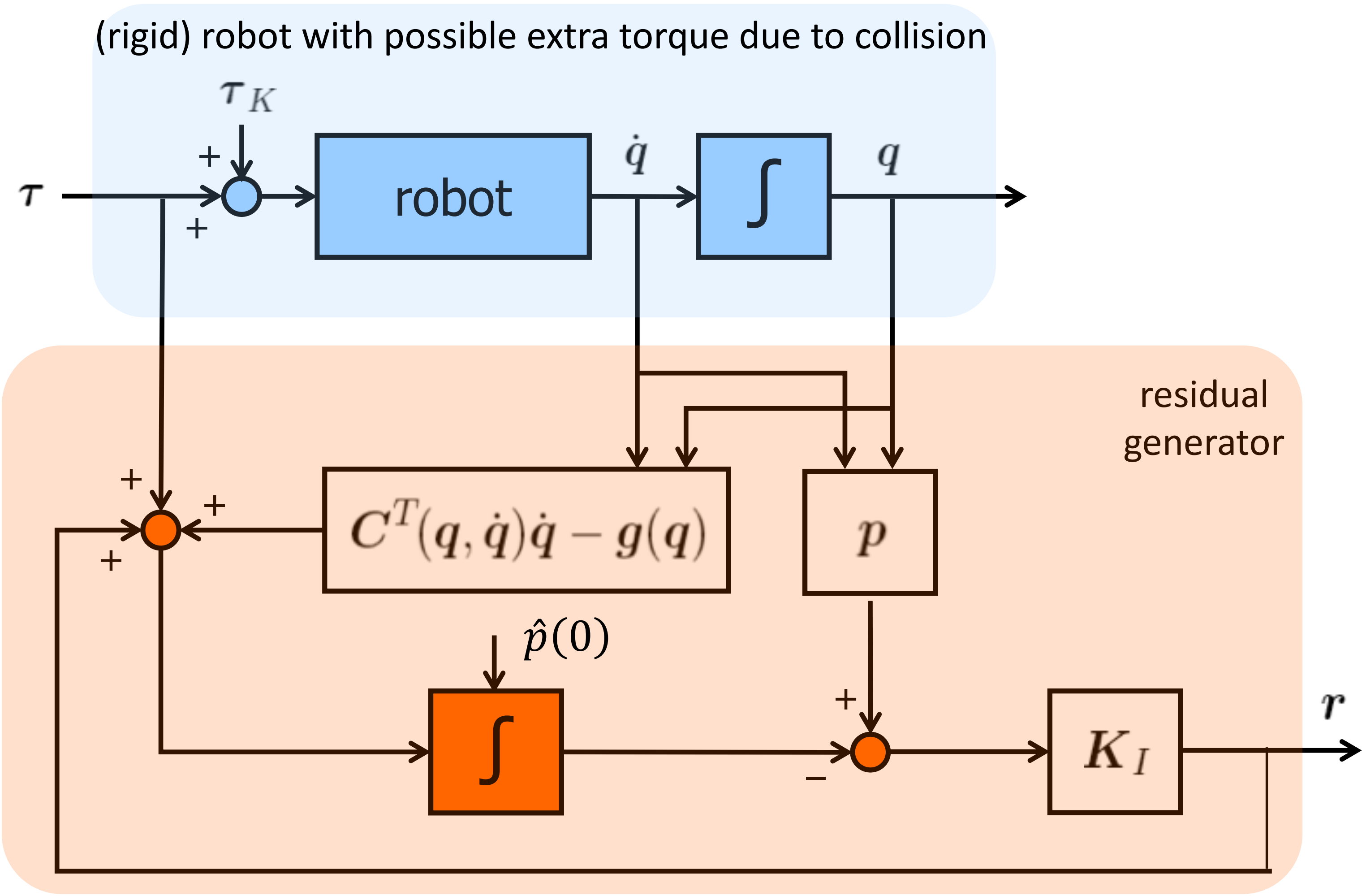


σ = energy-based scalar residual for detection

$\boldsymbol{r}$ = momentum-based vector residual for detection and isolation

Momentum-based residual

Block diagram for the generator of a vector residual signal (ICRA 2005, IROS 2006)



correct
initialization
$\hat{p}(0) = p(0)$

$$r(t) = K_I \left[p(t) - \int_0^t \left(\tau + C^T(q,\dot{q})\dot{q} - g(q) + r \right) ds - p(0) \right] \quad \Rightarrow \quad \dot{r} = -K_I r + K_I \tau_K$$

Collision detection and reaction

Residual-based experiments on DLR LWR-III (IROS 2006, IROS 2008)

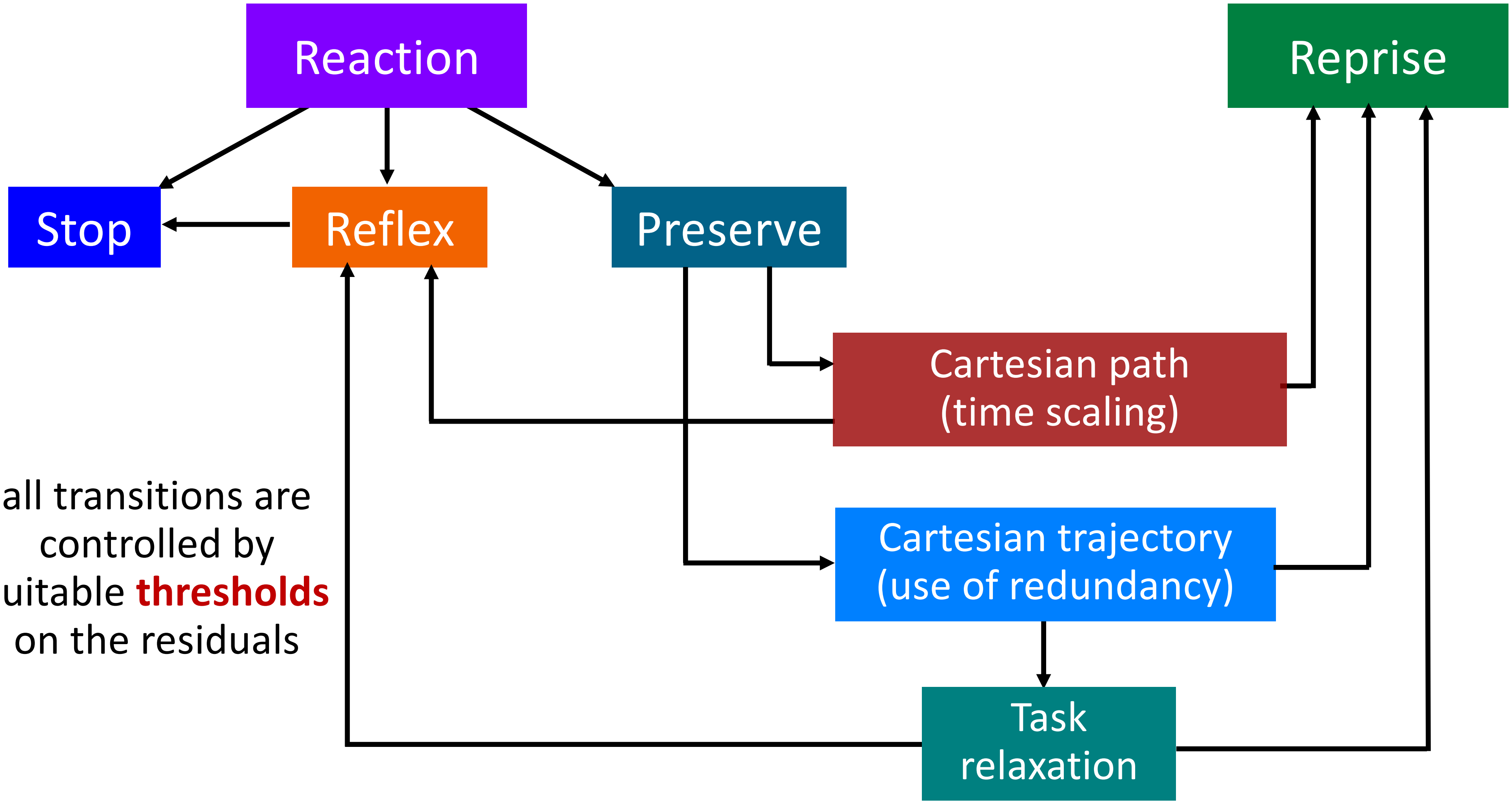
- collision detection followed by different reaction strategies
- zero-gravity behavior: gravity is always compensated first (by control)
- detection time: 2-3 ms, reaction time: + 1 ms

admittance mode	reflex torque	reflex torque
first impact at 60°/s		first impact at 90°/s
$\dot{\boldsymbol{q}}_r = \boldsymbol{K}_Q \boldsymbol{r}$	$\boldsymbol{\tau} = \boldsymbol{K}_R \boldsymbol{r}$	

Collision reaction

Portfolio of possible robot reactions

residual amplitude ∝ severity level of collision



all transitions are controlled by suitable **thresholds** on the residuals

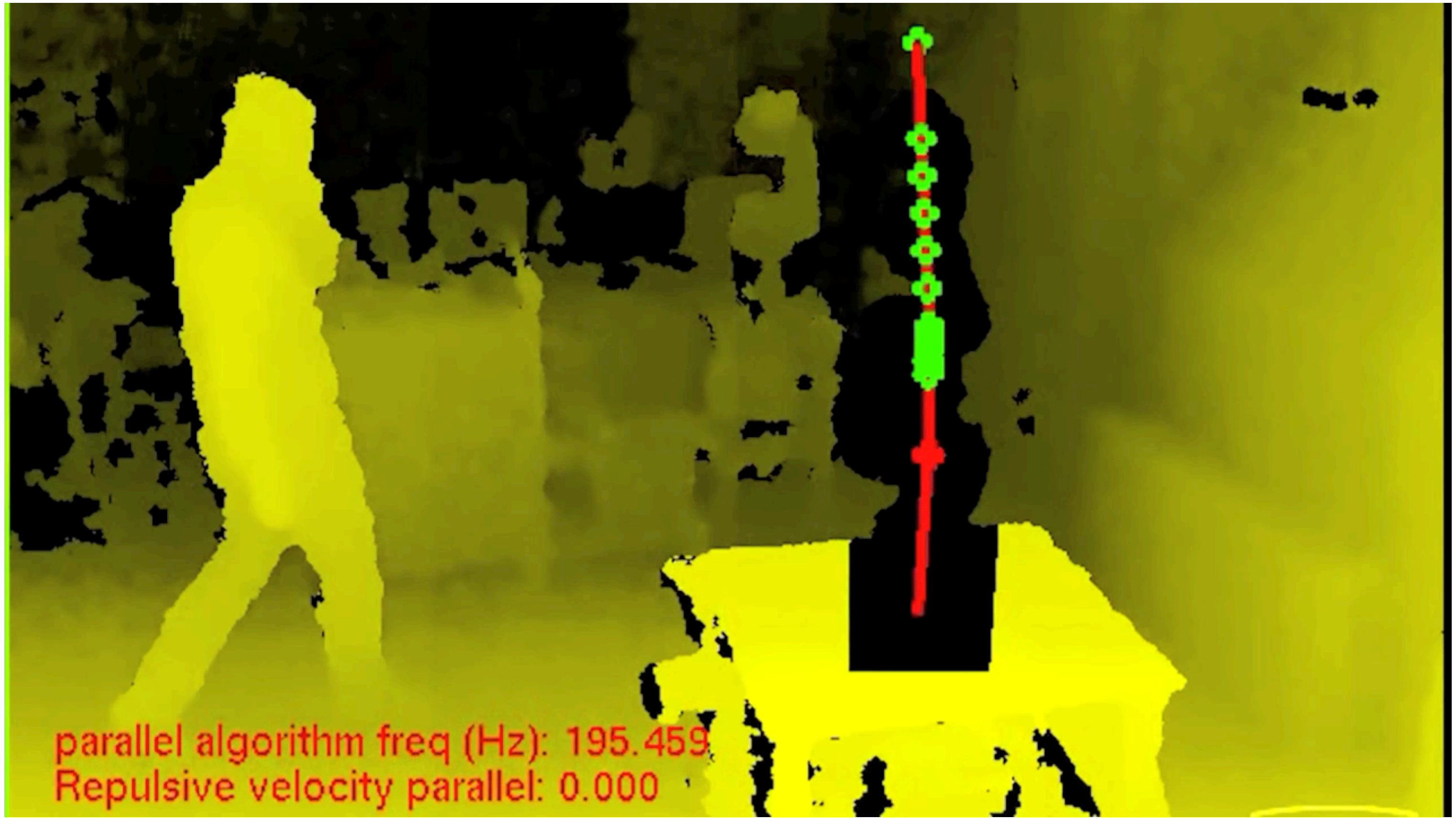
Use of kinematic redundancy

Robot reaction to collisions, in parallel with execution of original task (IROS 2017)

idle ⇔ relax ⇔ abort

Safe human-robot coexistence

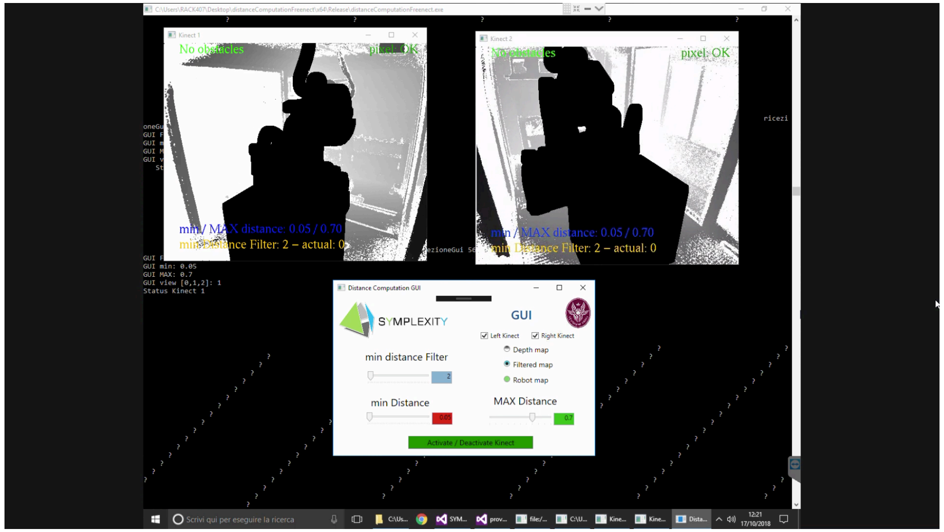
From finalist video (IROS 2013) [+ CUDA parallel computation (IROS 2017)]



- **distances** between robot [control] points and obstacles in **depth space** at 300Hz
- **coexistence** through standard collision avoidance algorithms

Safe coexistence in an industrial robotic cell

ABB IRB 4600 operation in an Abrasive Finishing cell with human access



depth images and GUI

- the robot is moving at max 100 mm/s
- no safety zones were defined in the ABB SafeMove software
- need a risk analysis & a mitigation plan on the two Kinects data and algorithm
  - e.g., when the view of one camera is obstructed, safety-certified laser sensors are used instead to estimate human distance (in a conservative way)

SYMPLEXITY

Force estimation for collaboration

Combining internal model and external sensing

- Task
  - **localize** (in the least invasive way) points on robot surface where contacts occur
  - **estimate** exchanged Cartesian forces
  - **control** the robot to react to these forces according to a desired behavior
- Solution idea
  - model-based residuals to **detect** contact, **isolate** colliding link, and **identify** the joint torques associated to the external contact force
  - depth sensor to **classify** human part in contact with the robot and **localize** the contact point on the robot structure (and the **contact Jacobian**)
  - **solve** a linear set of equations with the **residuals**, i.e., filtered estimates of joint torques resulting from contact forces/moments applied (anywhere) to the robot

$$\boldsymbol{r} \simeq \boldsymbol{\tau}_{ext} = \boldsymbol{J}_c^T(\boldsymbol{q})\boldsymbol{\Gamma}_c = \begin{pmatrix} \boldsymbol{J}_{L,c}^T(\boldsymbol{q}) & \boldsymbol{J}_{A,c}^T(\boldsymbol{q}) \end{pmatrix} \begin{pmatrix} \boldsymbol{F}_c \\ \boldsymbol{M}_c \end{pmatrix} \Rightarrow \begin{pmatrix} \widehat{\boldsymbol{F}}_c \\ \widehat{\boldsymbol{M}}_c \end{pmatrix} = \left(\boldsymbol{J}_c^T(\boldsymbol{q})\right)^{\#} \boldsymbol{r}$$

$$\Rightarrow \widehat{\boldsymbol{F}}_c = \left(\boldsymbol{J}_{Lc}^T(\boldsymbol{q})\right)^{\#} \boldsymbol{r}$$

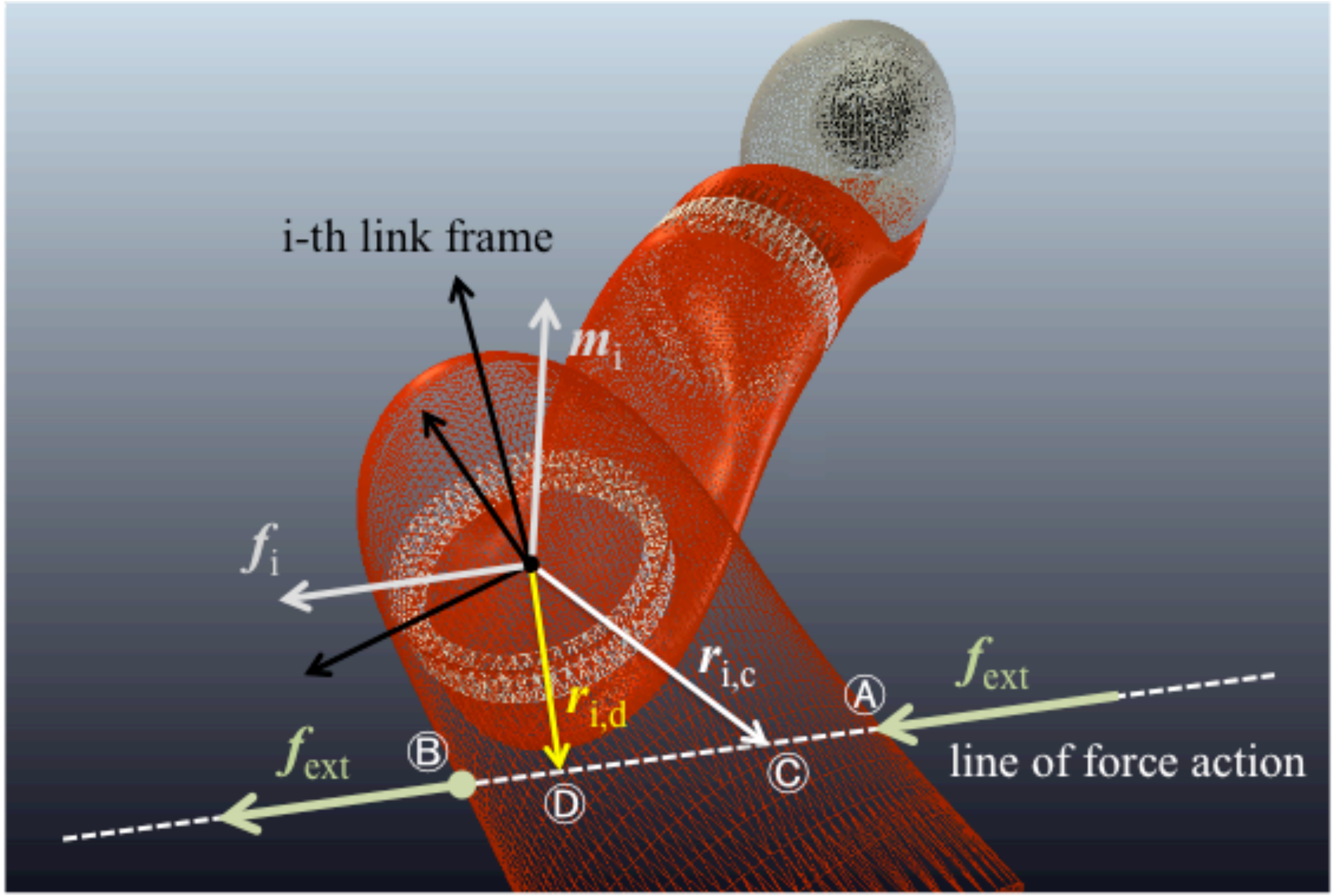
Control based on contact force estimation

Used within an admittance control scheme (IROS 2014)

Estimation of the contact force

Sometimes, even without external sensing (T-RO 2017)

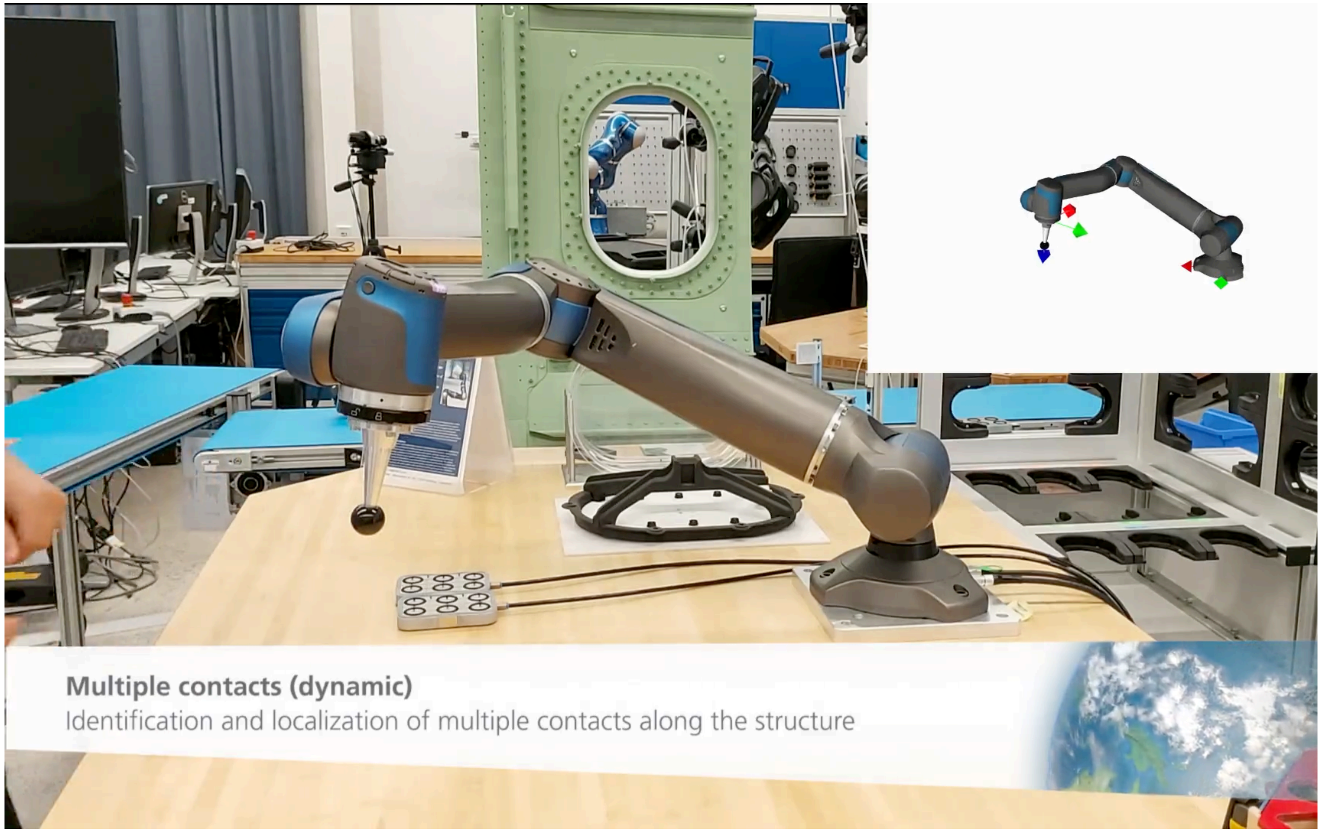
- if contact is sufficiently "down" the kinematic chain (≥ 6 residuals are available), estimation of pure contact forces needs **no external information** ...



Enhanced collision detection & identification

DLR SARA 7R robot with joint torque, base F/T and end-effector F/T sensors (ICRA 2021)

- generalized momentum-based residual, exploiting redundancy of sensing system
- handles multiple contacts, singularities, and external force/torque estimation



M. Iskandar, O. Eiberger, A. Albu-Schäffer, A. De Luca, A. Dietrich, "Collision detection and localization for the DLR SARA robot with sensing redundancy," ICRA 2021 Best HRI Paper Award Finalist

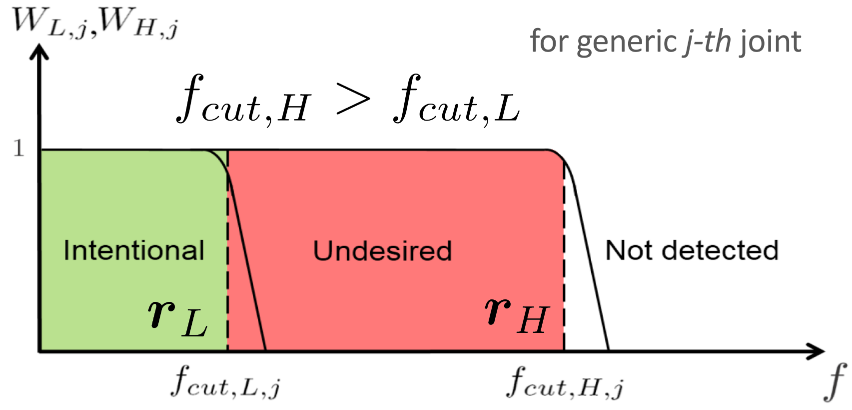
Collision or collaboration?

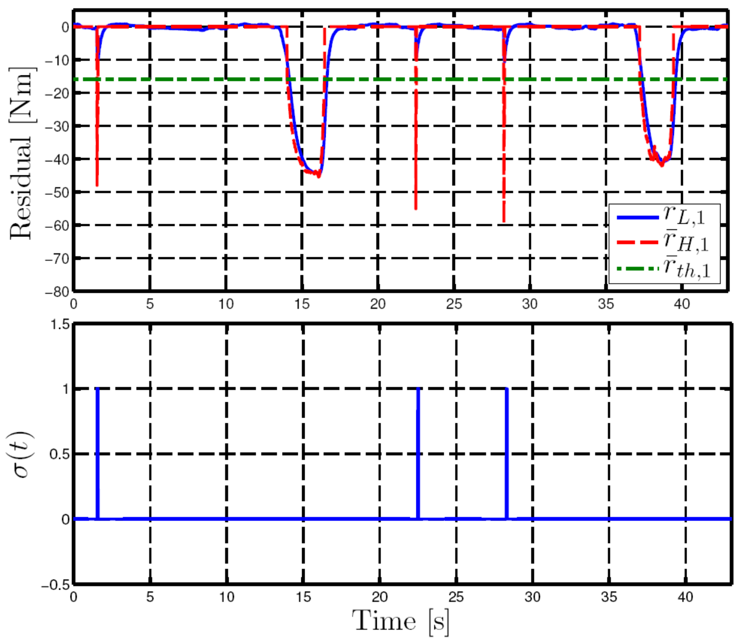
Distinguishing hard/accidental collisions and soft/intentional contacts

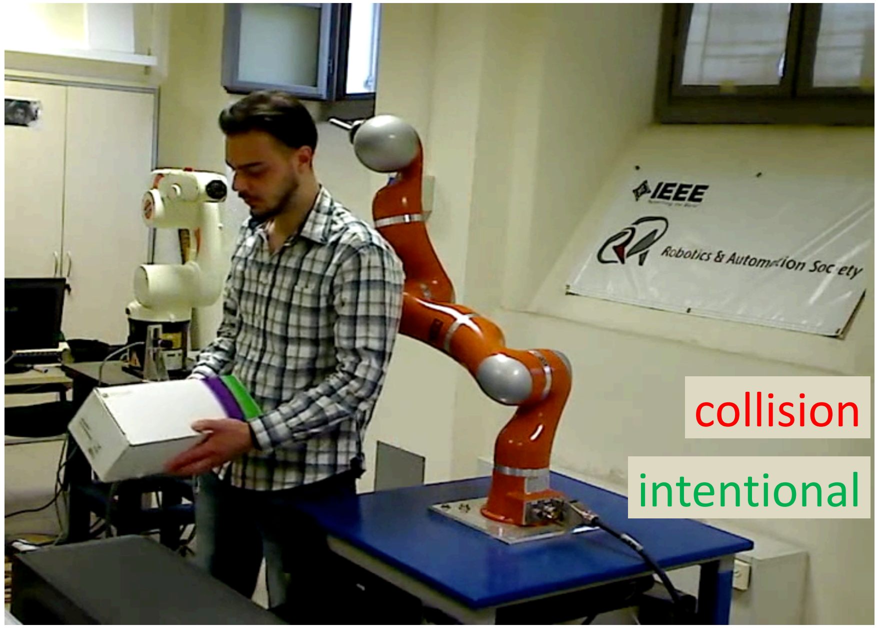
- using suitable low and high bandwidths for the residuals (first-order stable filters)

$$\dot{\boldsymbol{r}} = -\boldsymbol{K}_I \boldsymbol{r} + \boldsymbol{K}_I \boldsymbol{\tau}_K$$

- thresholds prevent false collision detections
- collision: stop & float ⇔ contact: collaborate







Collaboration control

Use of the estimate of external contact force for control (e.g., on a Kuka LWR)

- shaping the robot dynamic behavior in specific **collaborative tasks** with humans
  - joint carrying of a load, holding a part in place, whole arm **force** manipulation, ...
- robot motion controlled by
  - **admittance** control law (in **velocity FRI** mode)
  - **force**, **impedance** or **hybrid force-motion** control laws (in **torque FRI** mode)

  all implemented **at contact level**
- e.g., admittance control law using the estimated contact force
  - the scheme is realized at the single (or first) contact point
  - desired **velocity** of contact point taken proportional to (**estimated**) contact force

$$\dot{\boldsymbol{p}}_c = \boldsymbol{K}_a \boldsymbol{F}_a, \qquad \boldsymbol{K}_a = k_a \boldsymbol{I} > 0$$

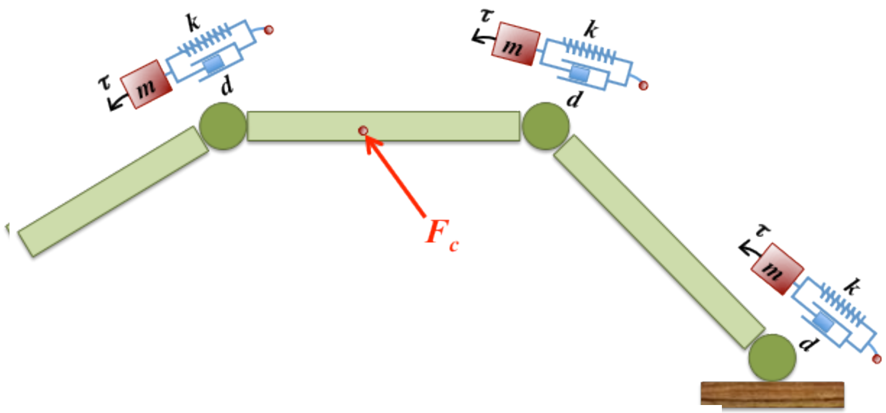
$$\boldsymbol{F}_a = \widehat{\boldsymbol{F}}_c + \boldsymbol{K}_p (\boldsymbol{p}_d - \boldsymbol{p}_c), \qquad \boldsymbol{K}_p = k_p \boldsymbol{I} > 0$$

↖ initial contact point position when interaction begins

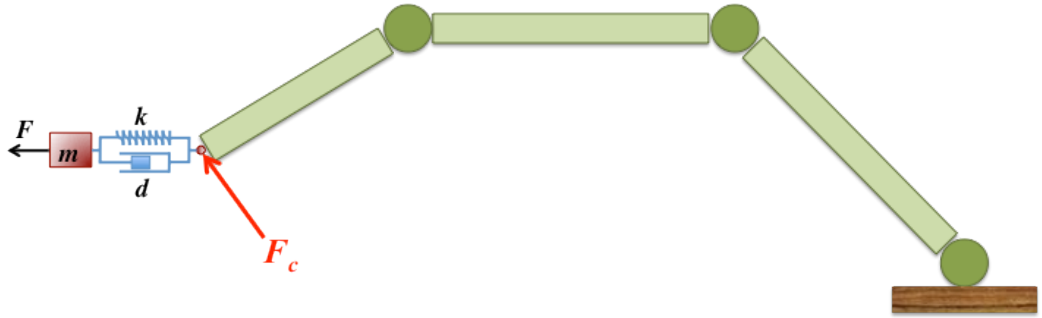
Impedance-based control of interaction

Reaction to contact forces by generalized impedance —at different levels

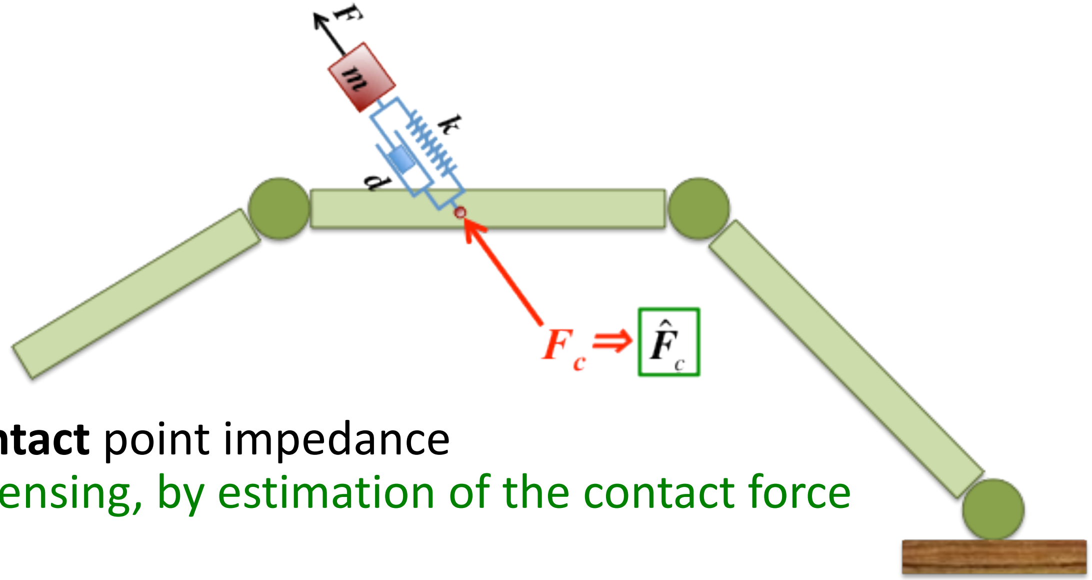
consider a fully rigid robot



Joint impedance
needs joint torque sensors



Cartesian impedance
needs F/T sensor



Contact point impedance
without force/torque sensing, by estimation of the contact force

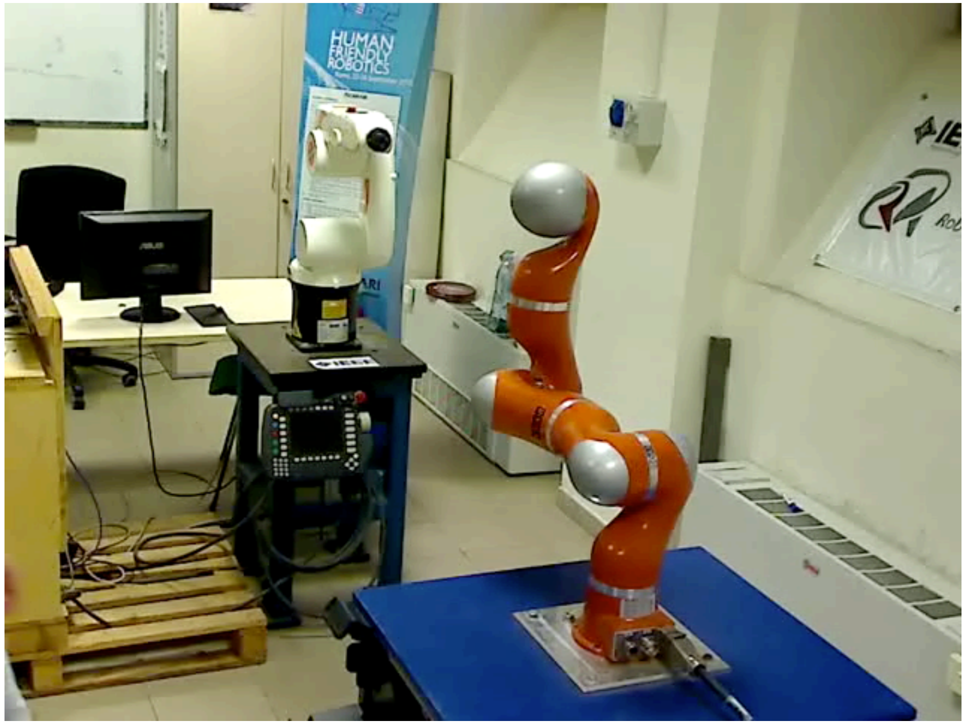
Control of generalized impedance

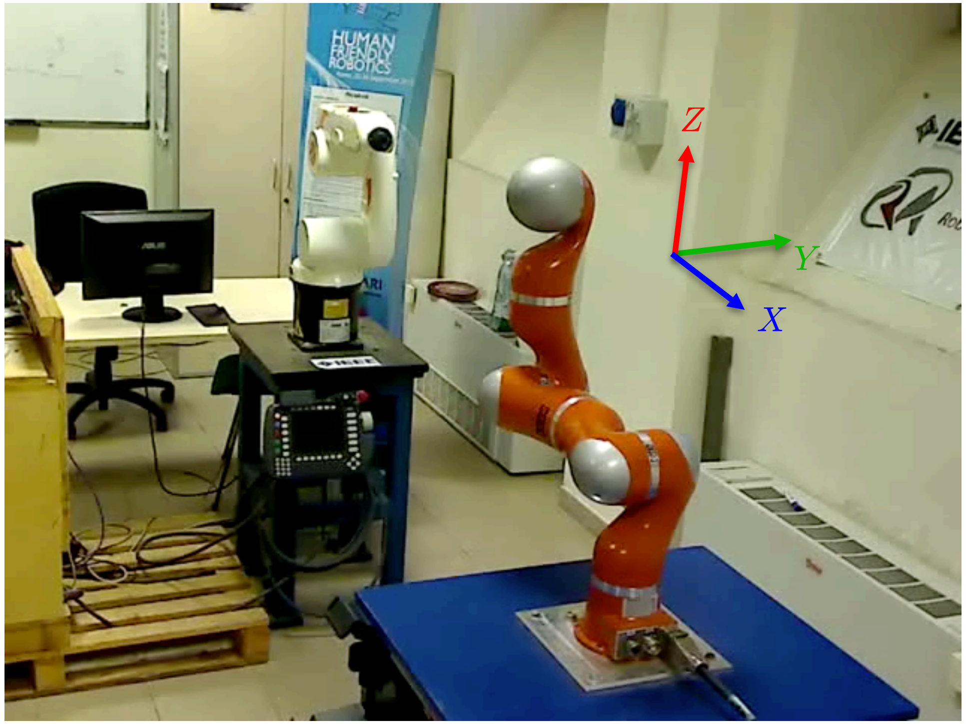
HR collaboration at the contact level (ICRA 2015)

natural (unchanged) robot inertia at the contact

$$\boldsymbol{M}_d = \left(\boldsymbol{J}_c \boldsymbol{M}^{-1} \boldsymbol{J}_c^T\right)^{-1}$$

assigned robot inertia at the contact
with different desired masses along X, Y, Z





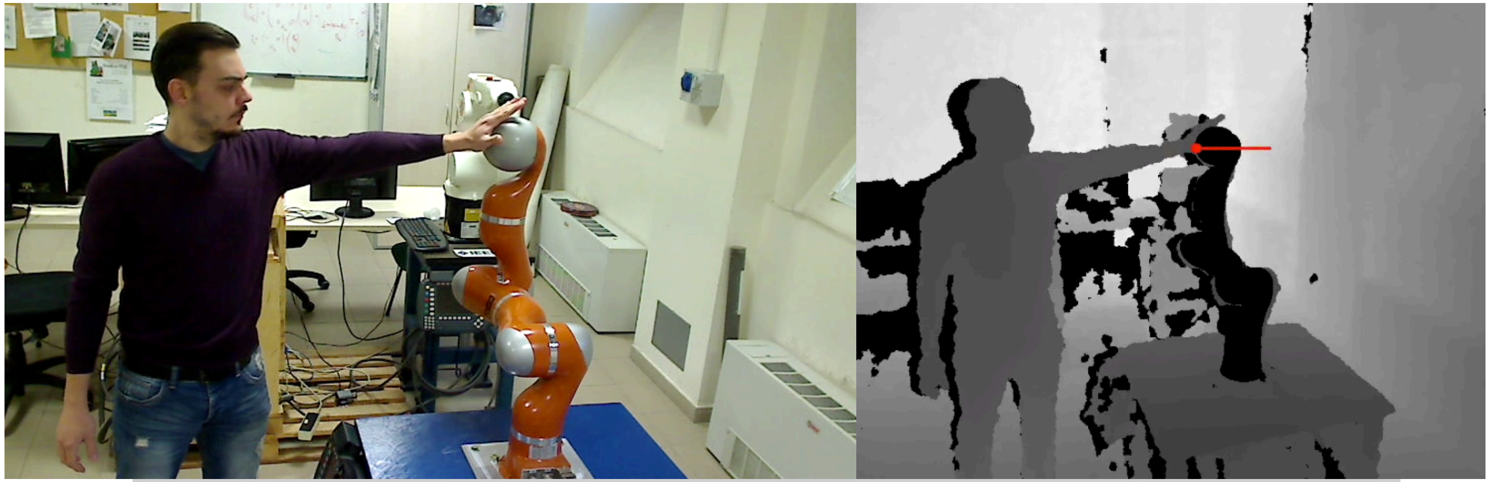
contact force **estimates** are used here **only** to detect and localize contact in order to start a collaboration phase

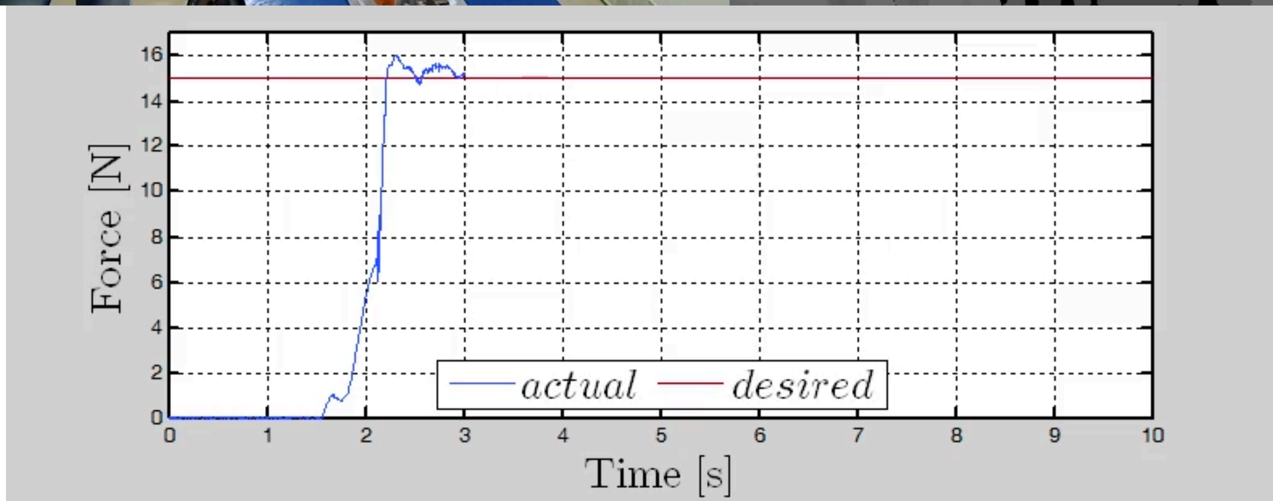
contact force **estimates** used **explicitly** in control law to modify robot inertia at the contact ($M_{d,X} = 20$, $M_{d,Y} = 3$, $M_{\mathrm{d},Z} = 10$ [kg])

Contact force regulation with virtual force sensing

Human-robot collaboration in torque control mode (ICRA 2015)

- contact force estimation & control (any place/any time)





ICRA 2015 trailer (at 3’26’’): https://youtu.be/glNHq7MpCG8 (Italian); https://youtu.be/OM_1F33fcWk (English)

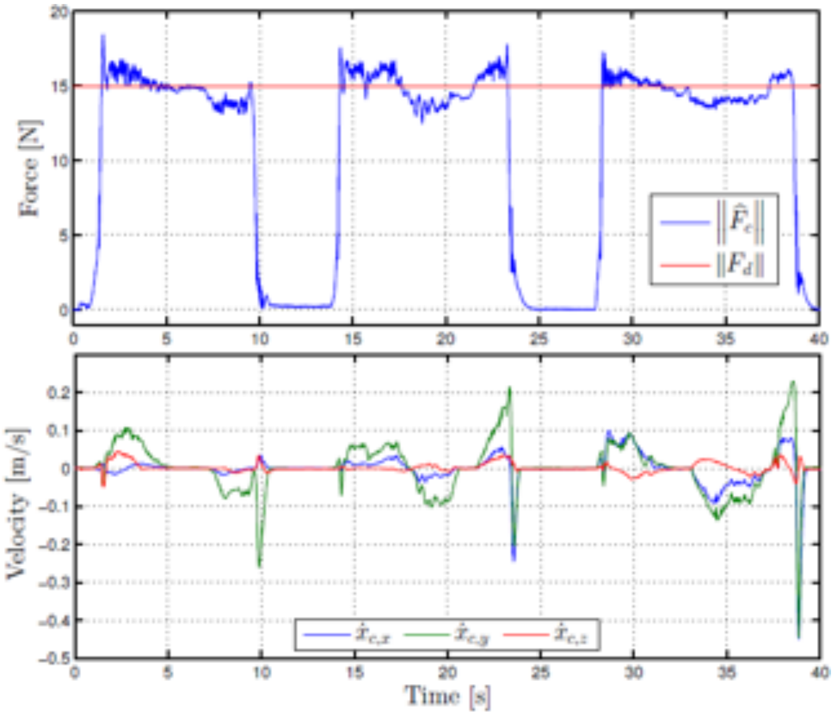
Control of generalized contact force

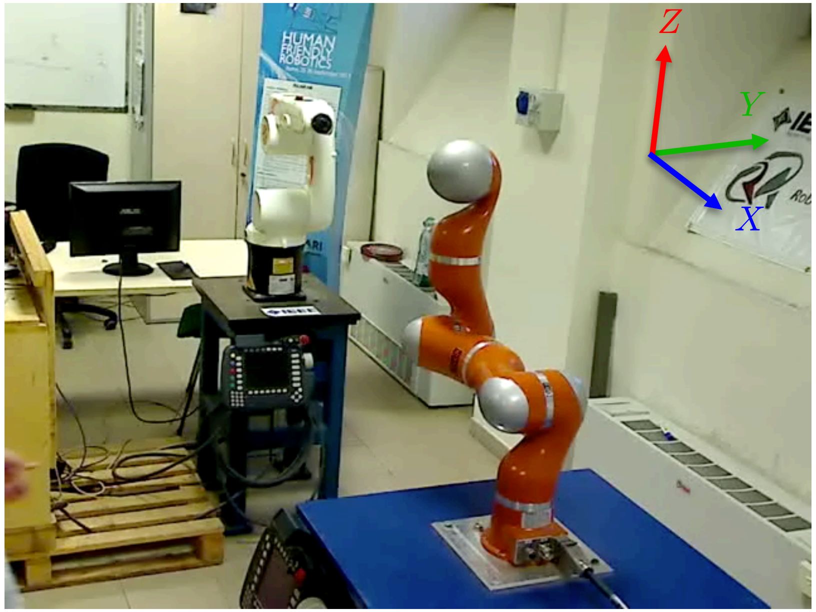
Task-compatible force control scheme (ICRA 2015)

- regulation of the **norm** of the contact force along the instantaneous **direction** of the estimated contact force

$$F_{d,x} = 15\frac{\widehat{F}_{c,x}}{\|\widehat{\boldsymbol{F}}_c\|}, \quad F_{d,y} = 15\frac{\widehat{F}_{c,y}}{\|\widehat{\boldsymbol{F}}_c\|}, \quad F_{d,z} = 15\frac{\widehat{F}_{c,z}}{\|\widehat{\boldsymbol{F}}_c\|} \quad \Leftrightarrow \quad \|F_d\| = 15 \text{ [N]}$$

- in static conditions, the force control law is able to regulate contact forces **exactly**

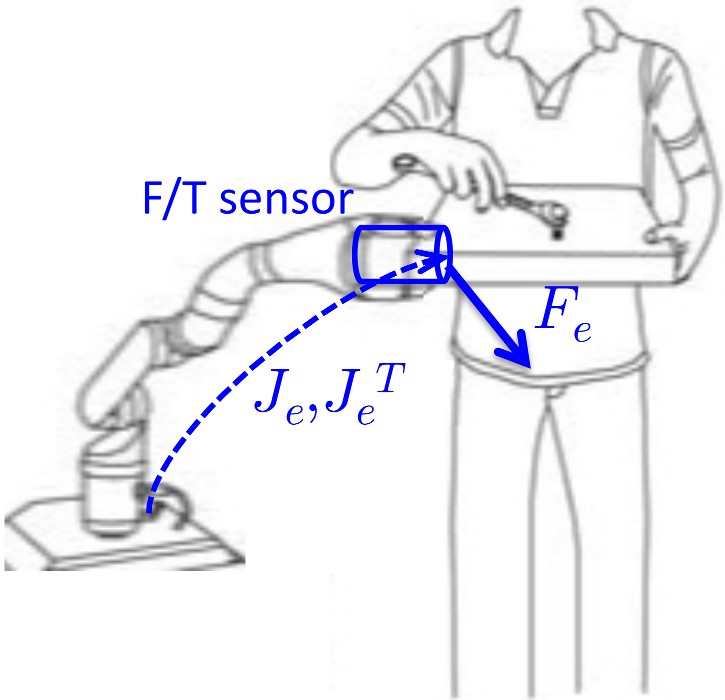




task-compatible control of contact force

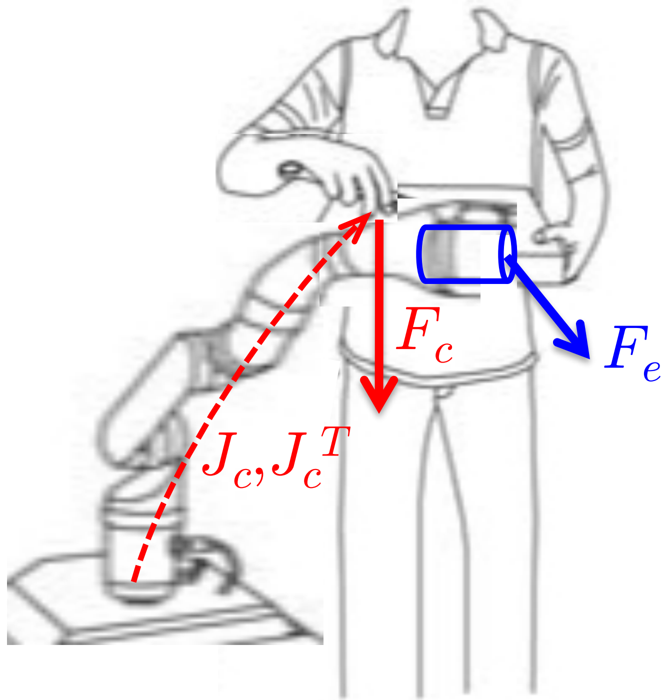
Scenario for HRC in manual polishing

Distinguishing different contact forces (with F/T sensor)



Force/Torque (F/T) sensor at wrist
- manual polishing force is **measured**
- end-effector Jacobian is **known**

contact force at unknown location
- **not** measurable by the F/T sensor
- possibly applied by the human **while** manipulating the work piece held by robot
- contact Jacobian is **not** known



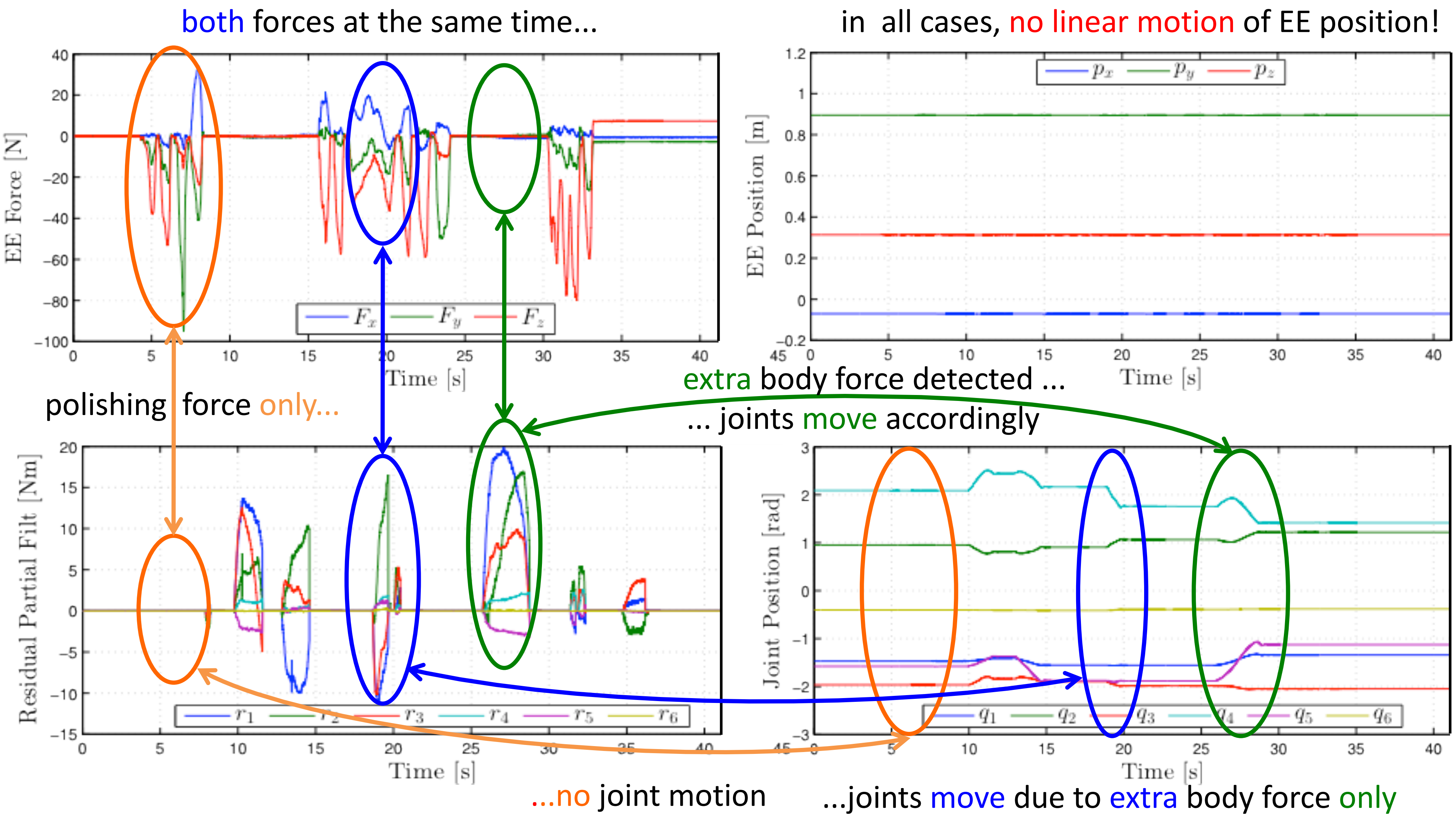
HRC phase with UR10 robot

Experimental results (Mechatronics 2018)

with F/T sensor, using our residual method

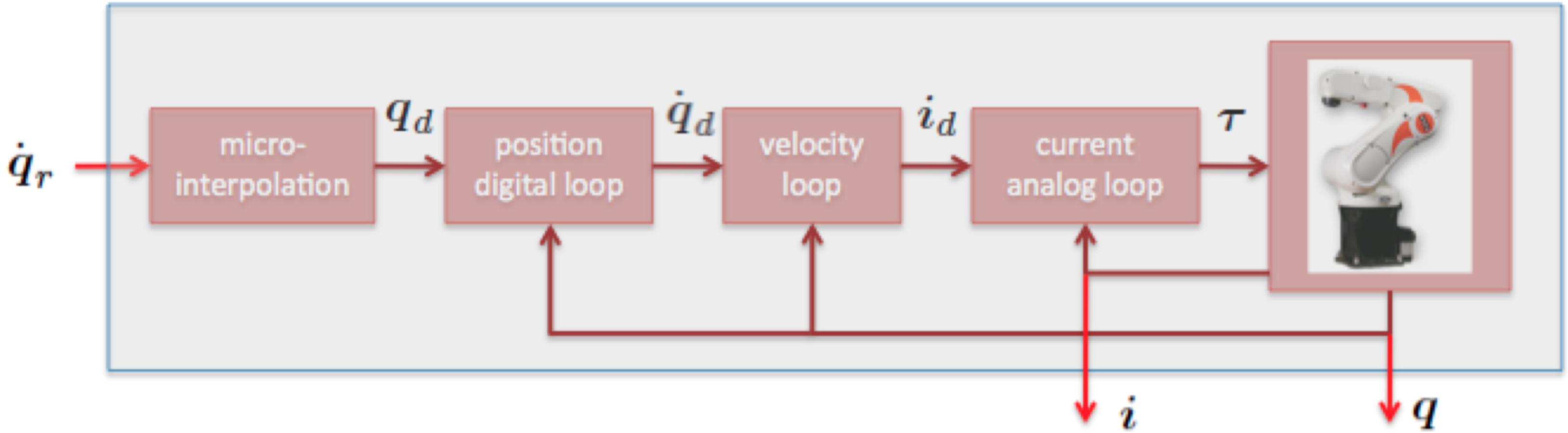
HRC phase with UR10 robot

Experimental results (separating F/T measures from residuals)

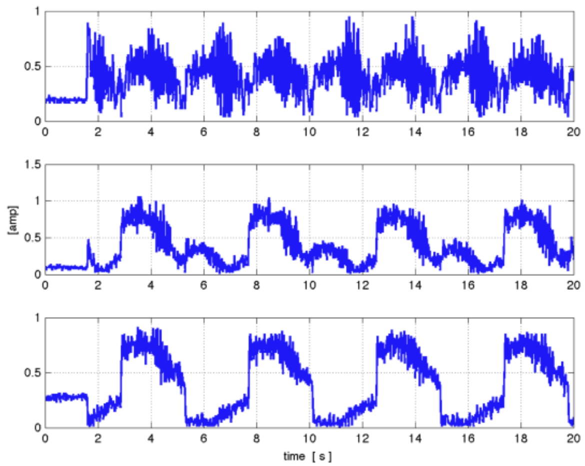


HRC under a closed control architecture

KUKA KR5 Sixx R650 robot



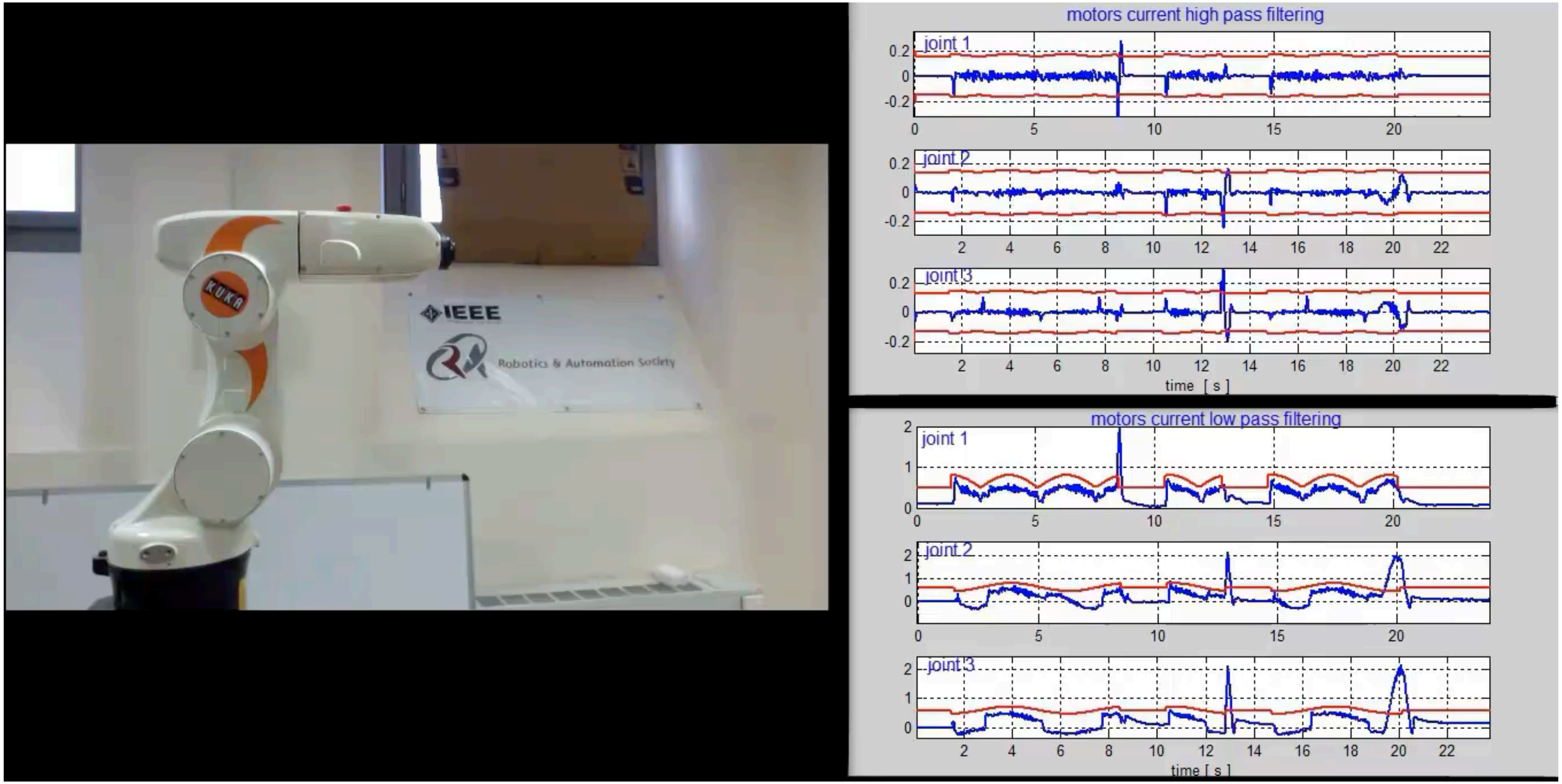
- low-level motor control laws not known and not accessible
- user programs based on exteroceptive sensors (vision, Kinect, F/T sensor) implemented on external PC and communicate via RSI (RobotSensorInterface) with KUKA controller every 12 ms
- available robot measures: joint positions (by encoders) and (absolute value of) applied motor currents
- the only user commands for the controller are velocity or position references in joint (or Cartesian) space



typical motor currents on first three joints

Distinguish accidental collisions from intentional contacts

… and then either stop or start to collaborate (ICRA 2013)



using high-pass and low-pass filtering of motor currents
— here collaboration mode is manual guidance of the robot

Conclusions

Toward a safer and efficient control of physical human-robot collaboration

- safe human-robot coexistence and collaboration, based on a hierarchy of consistent, controlled behaviors of the robot
  - (sensorless) collision detection and reaction with model-based residuals
    - extended to multiple robot types: UAVs, humanoids, soft robots, …
  - real-time collision avoidance based on data processed in depth space
  - distinguishing intentional/soft contacts from accidental/hard collisions
  - estimation of contact force and location, by combining inner/outer sensing
  - “control bricks” for collaborative tasks
    - admittance/impedance/force/hybrid laws, generalized at the contact level
  - useful behaviors can be obtained also with limited model information
- many interesting research problems ahead
  - human motion and intention prediction, merging models and data
  - integration with AI-based cognitive HRI modules

with JPL around the world …

New Orleans, 2004

Toulouse, 2013

Washington, 2002

Shanghai, 2011

Anchorage, 2010