Robotics Research Jam Session – Midsummer 2019

Pisa, June 19, 2019

Centro E. Piaggio
bioengineering and robotics research center

Advances in Control of Human-Robot Collaboration @DIAG

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SAPIENZA
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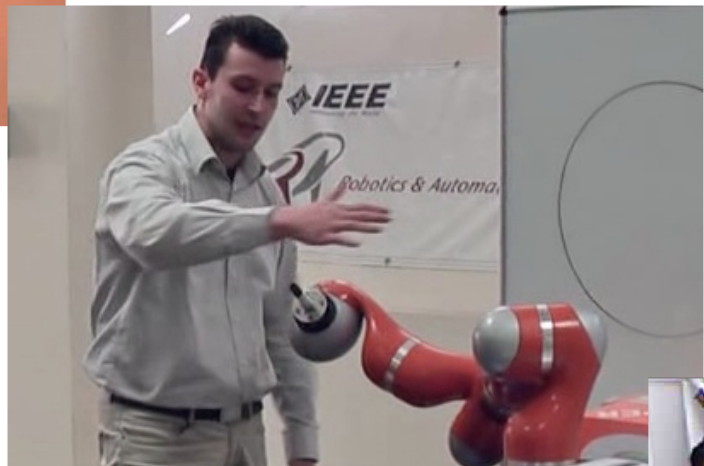
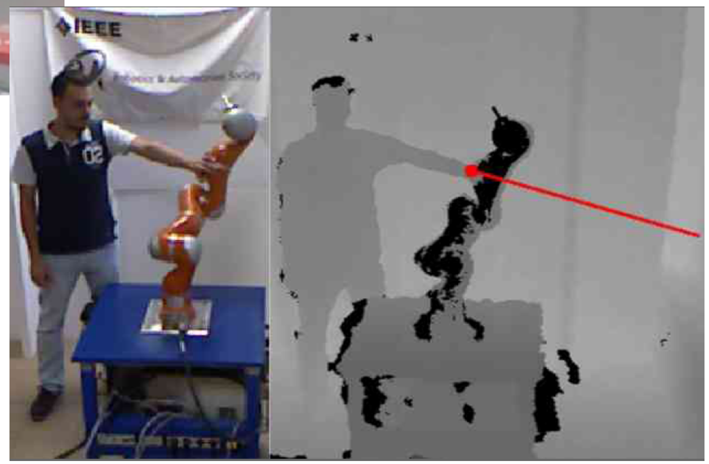
Handling of collisions and intentional contacts

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
(with or **without a F/T** sensor)
for human-robot collaboration

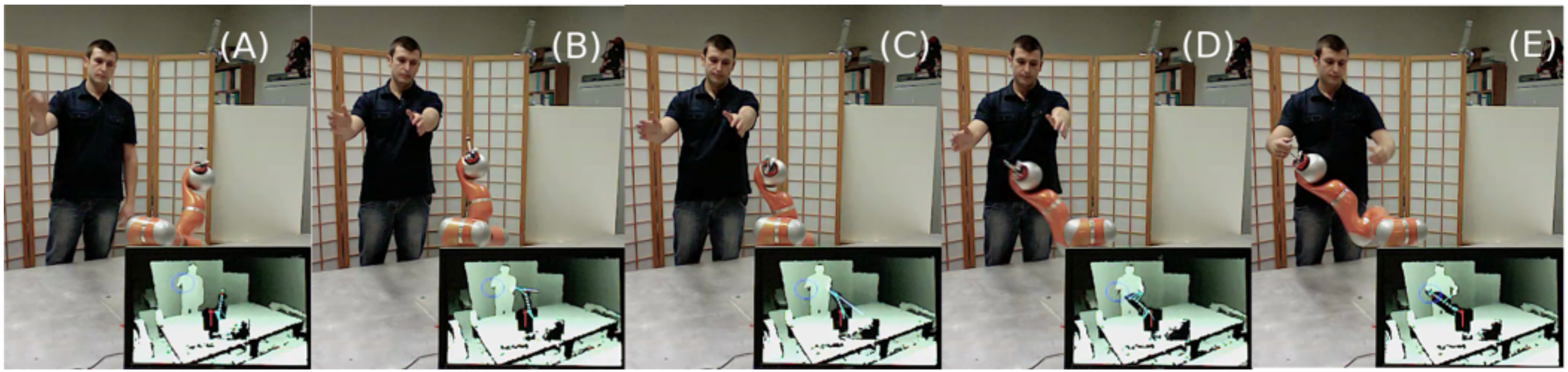
A control architecture for physical HRI

Hierarchy of consistent behaviors (BioRob 2012)

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

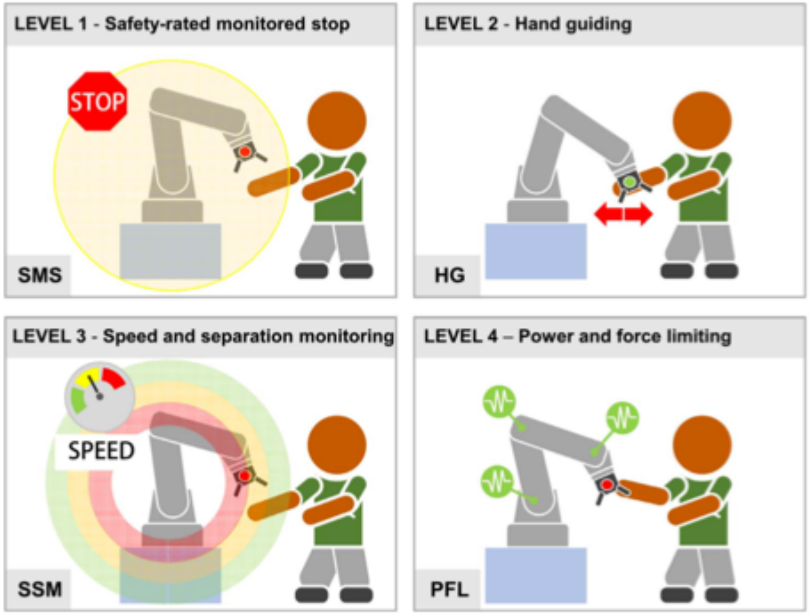
Coexistence is the robot capability of sharing the workspace with humans (**collision avoidance**)

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



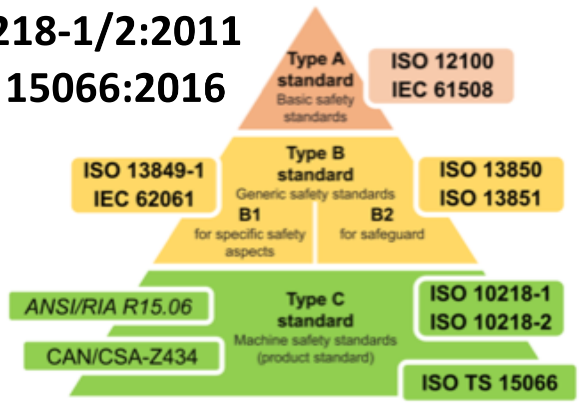
A control architecture for physical HRI

Relation with ISO Standard 10218 and Technical Specification 15066



	Speed	Separation distance	Torques	Operator controls	Main risk reduction
SAFETY Safety-rated monitored stop COEXISTENCE	Zero while operator in CWS	Small or zero	Gravity + load compensation only	None while operator in CWS	No motion in presence of operator
Hand guiding COLLABORATION	Safety-rated monitored speed	Small or zero	As by direct operator input	E-stop; Enabling device; Motion input	Motion only by direct operator input
Speed and separation monitoring COEXISTENCE	Safety-rated monitored speed	Safety-rated monitored distance	As required to execute application and maintain min separation distance	None while operator in CWS	Contact between robot and operator prevented
Power and force limiting COLLABORATION	Max determined by RA to limit impact forces	Small or zero	Max determined by RA to limit static forces	As required by application	By design or control, robot cannot impart excessive force

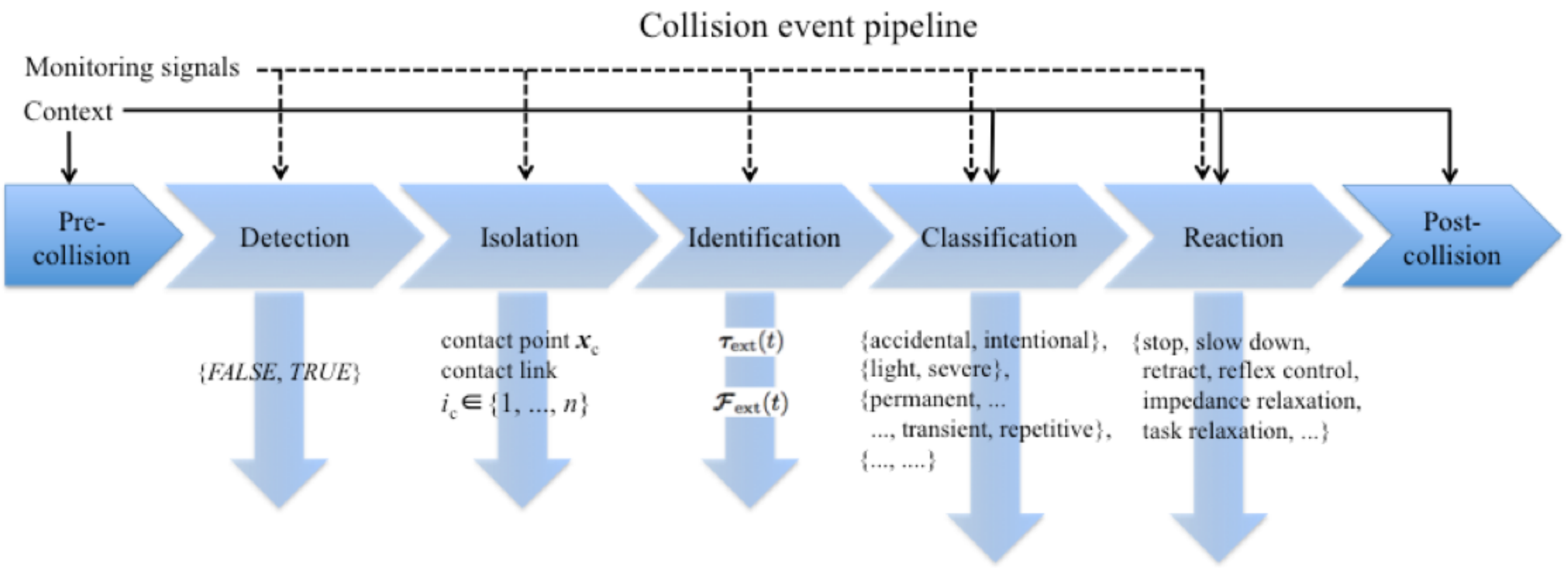
ISO 10218-1/2:2011
ISO/TS 15066:2016



- collision detection and reaction
- workspace sharing
  - with collision avoidance
- coordinated motions & actions
  - with/without contact

Collision event pipeline

Haddadin, De Luca, Albu-Schäffer (T-RO 2015)

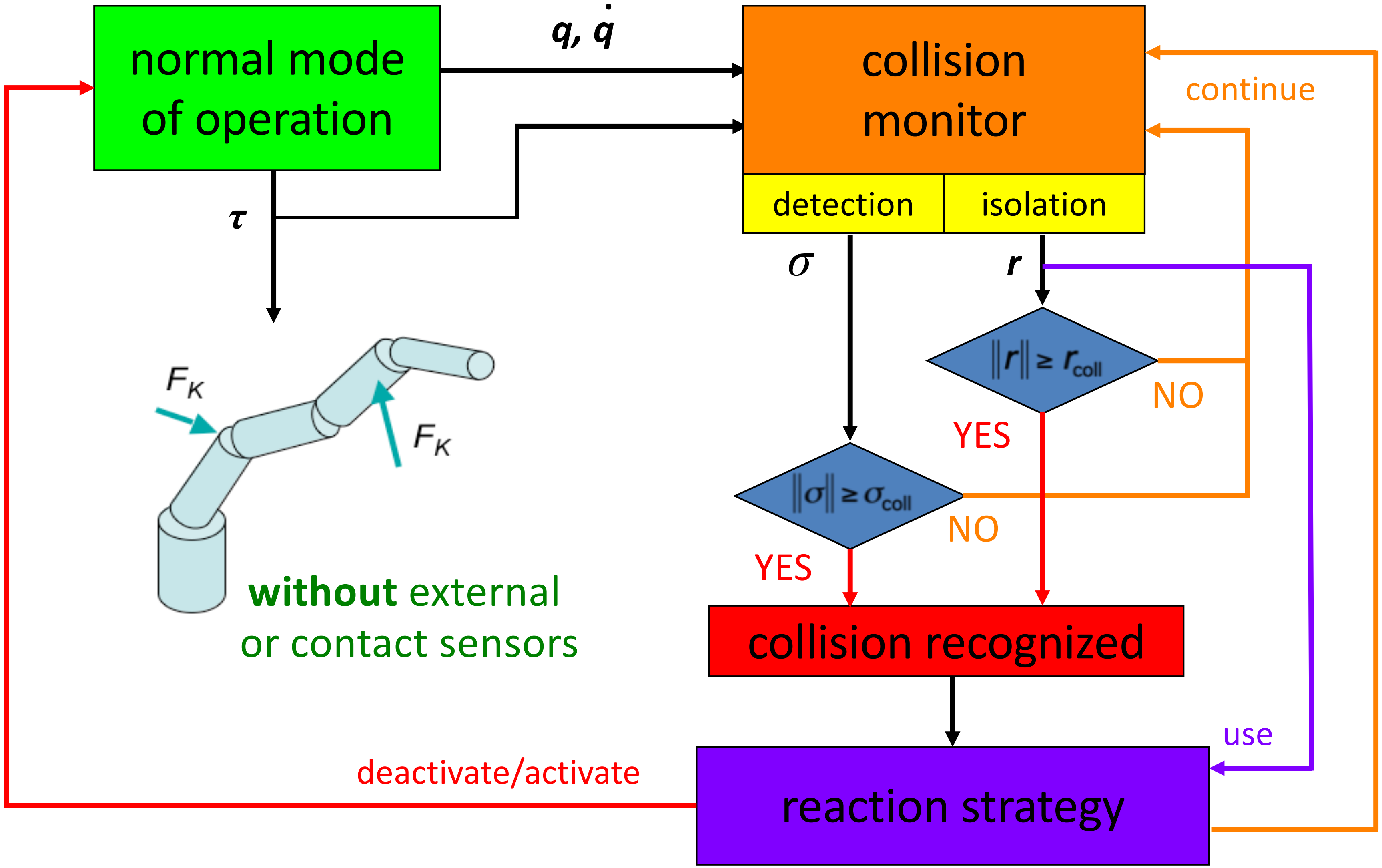


Monitoring signals can be generated from sensors or models (signal- or model-based methods)

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

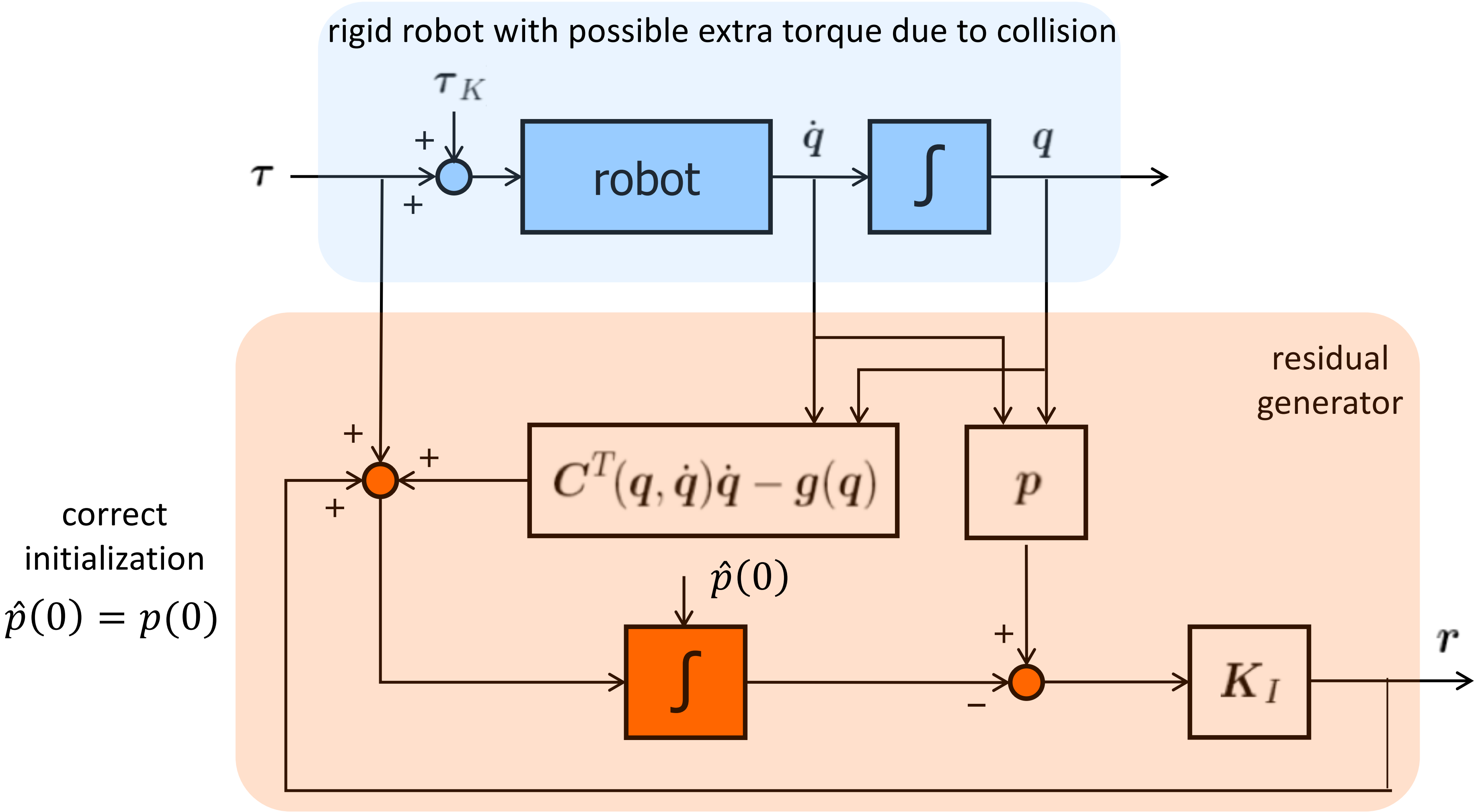
Monitoring robot collisions

Applies equally to rigid and elastic joints, with and without joint torque sensing



Momentum-based residual

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



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

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

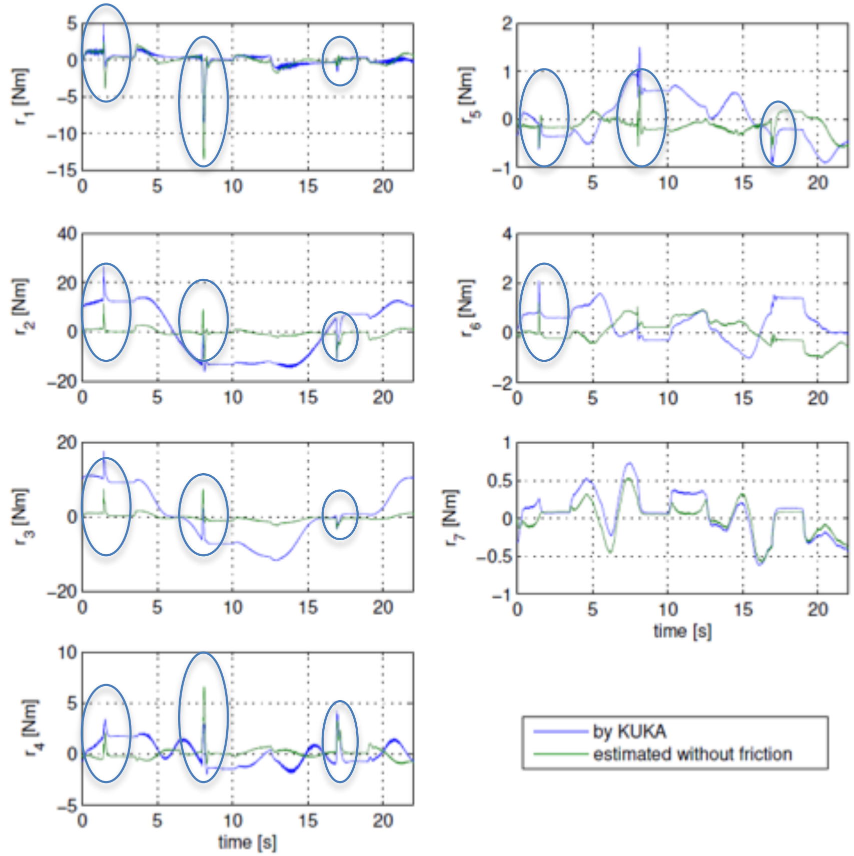
3 videos

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

Sensitivity to payload changes/uncertainty

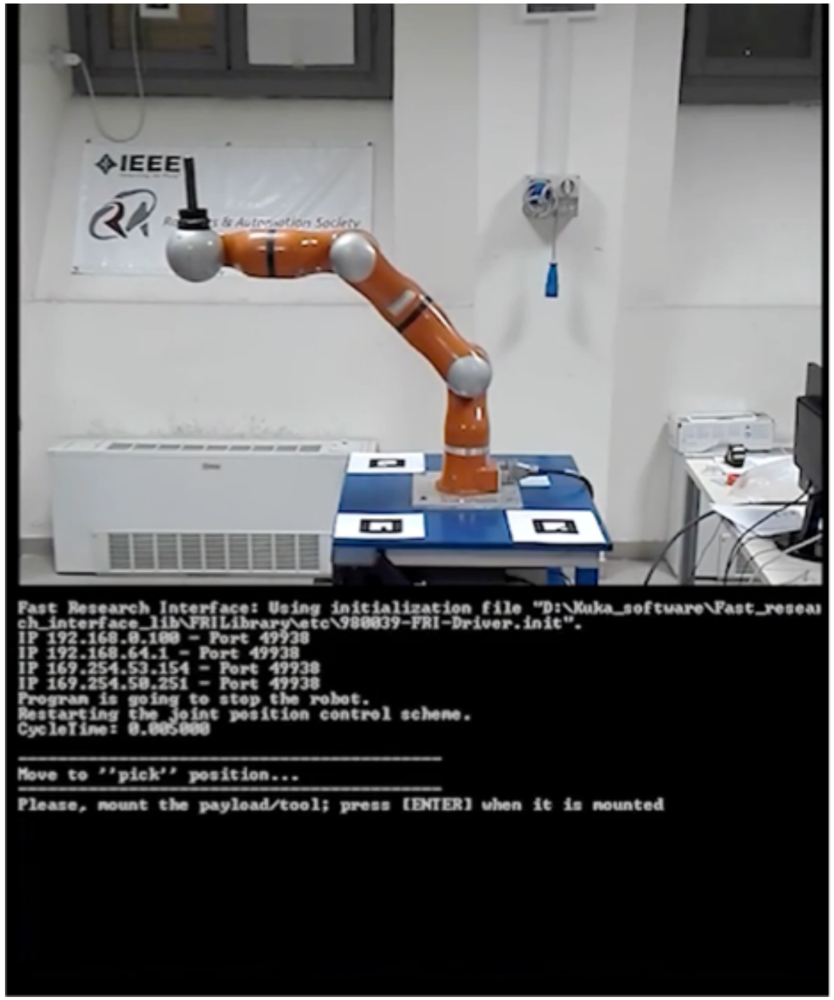
Collision detection and isolation after few moves for identification (IROS 2017)

residuals with online estimated payload after 10 positioning



the three collisions are detected by our residual when exceeding a threshold of 2 Nm

https://youtu.be/fNP6smdp7aE



video

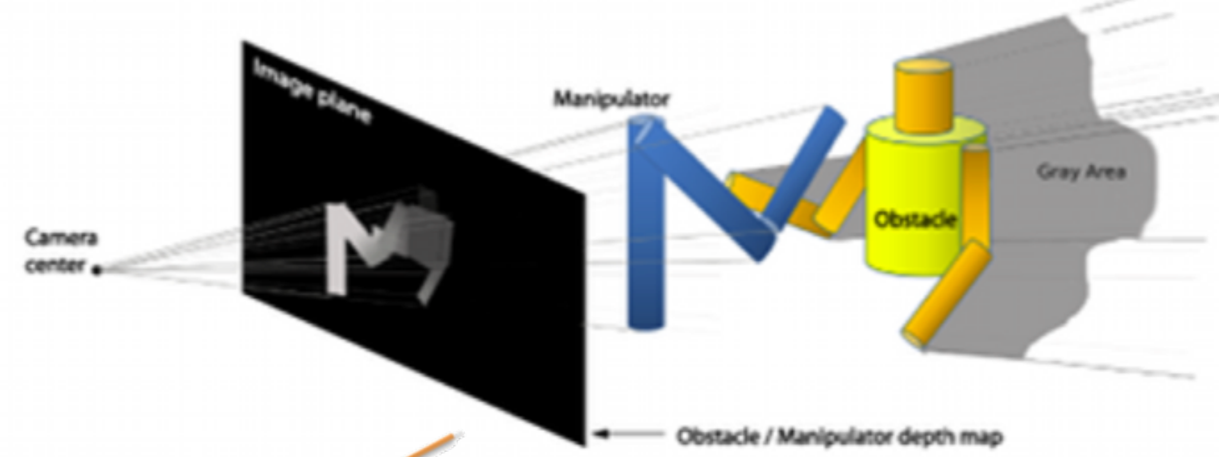
Collision avoidance working in depth space

Efficient robot-obstacle distance computations in a 2 ½ space (ICRA 2012)

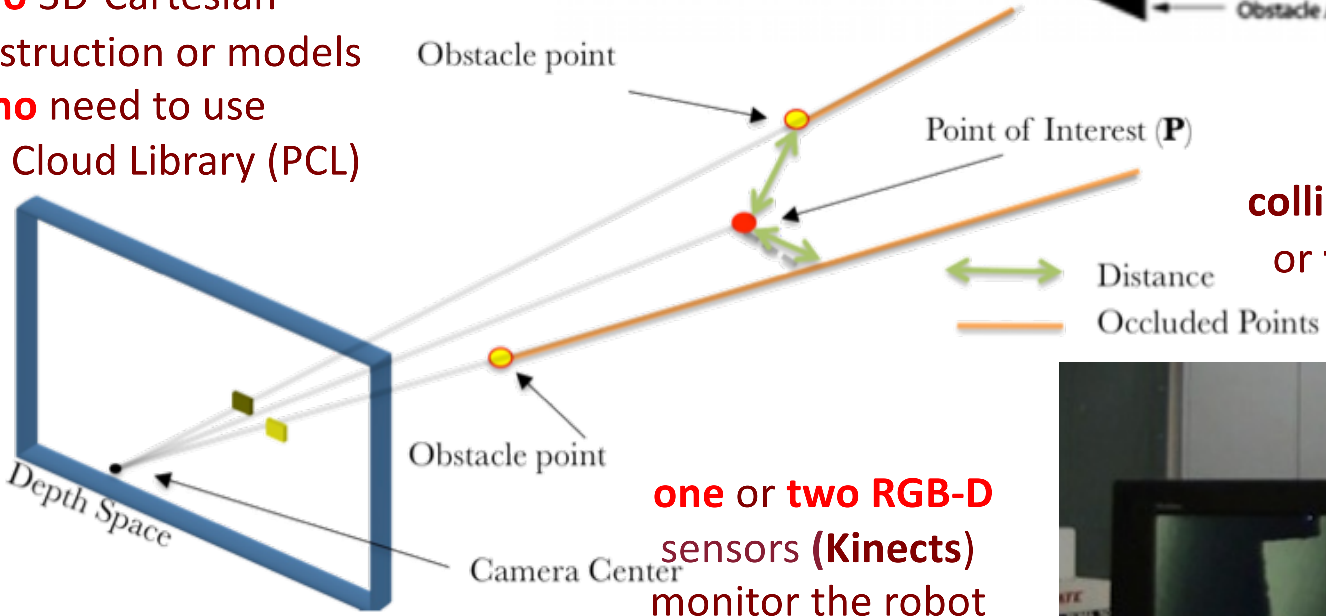
$$p_x = \frac{x_C f s_x}{z_C} + c_x$$

$$p_y = \frac{y_C f s_y}{z_C} + c_y$$

$$d_p = z_C$$

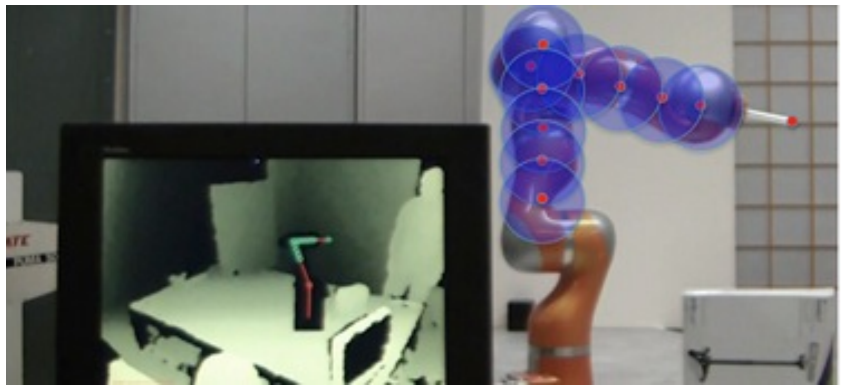


no 3D-Cartesian reconstruction or models
no need to use Point Cloud Library (PCL)



use distance, e.g., with artificial potentials, for **collision avoidance** during motion or **to slow down/stop** the robot

one or **two RGB-D** sensors **(Kinects)** monitor the robot workspace **@ 300 Hz** with minimal gray areas

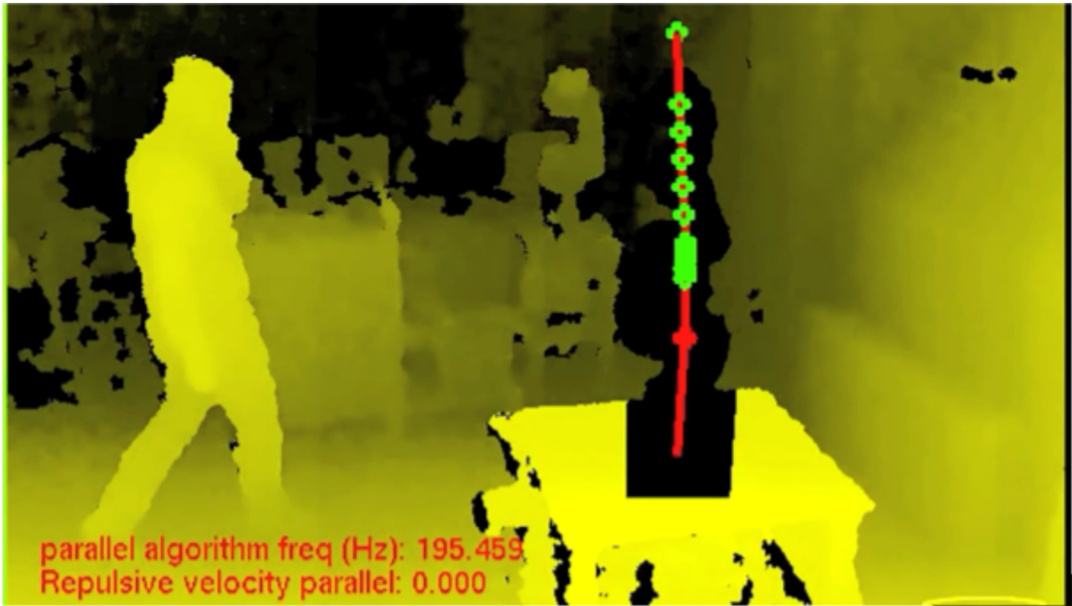


see also the video
https://youtu.be/iapfbAfklw4

Safe physical human-robot interaction

Excerpts from the finalist video at IROS 2013

SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction



coexistence through collision avoidance

https://youtu.be/pIlhY8E3HFg

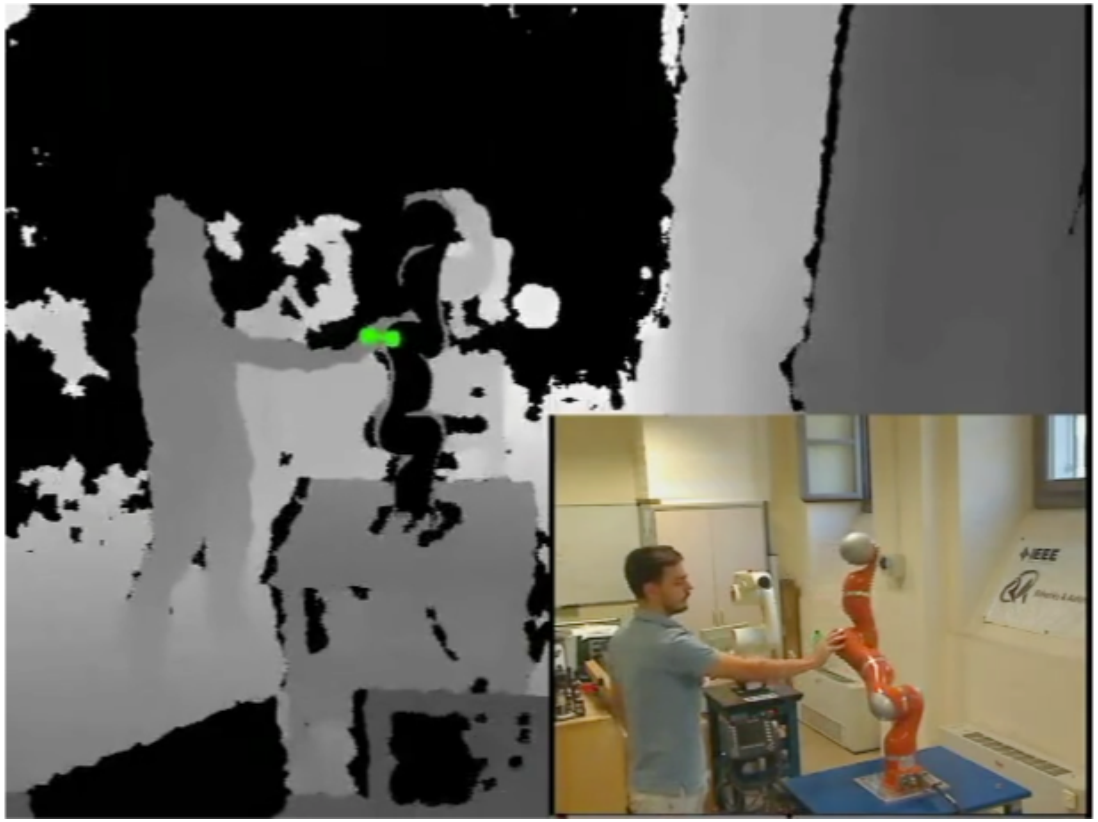
2 videos

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

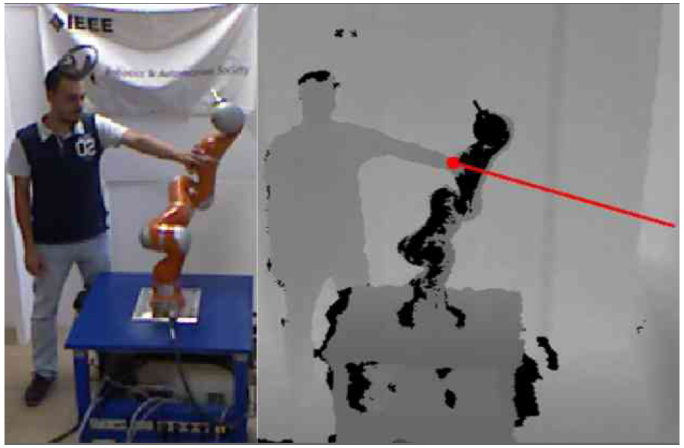
Distance and contact estimation

Using Kinect, CAD model, distance computation, and residual to localize contact (early 2014)

- when the residual indicates a contact/collision (and colliding link), the **vertex** in the robot CAD surface model **with minimum distance** is taken as the contact point
- algorithm applied here in parallel to both left and right hand (no other body parts)



video

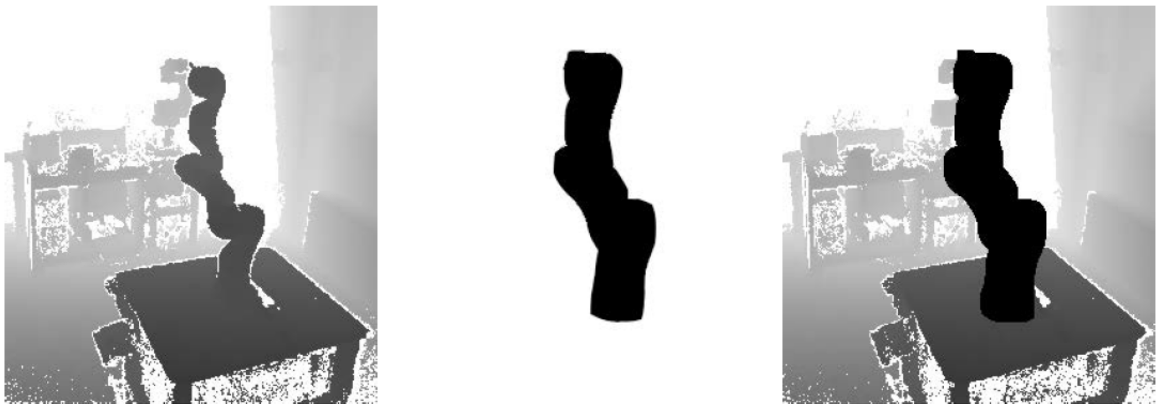


Contact point localization

CUDA framework (IROS 2017)

Real-time contact point localization

- the algorithm is based on distance computation in depth space, taking advantage of a **CUDA framework** for massively parallel **GPU** programming
- processing of three 2.5D images:
  - real depth image I_r , captured by a RGB-D sensor (a Kinect)
  - virtual depth image I_v, containing only a projection of the robot CAD model
  - filtered depth image $I_f = f(I_r, I_v)$, containing only the obstacles



- **distance computation** (in depth space) between all robot points in the virtual depth image and all obstacle points in the filtered depth image

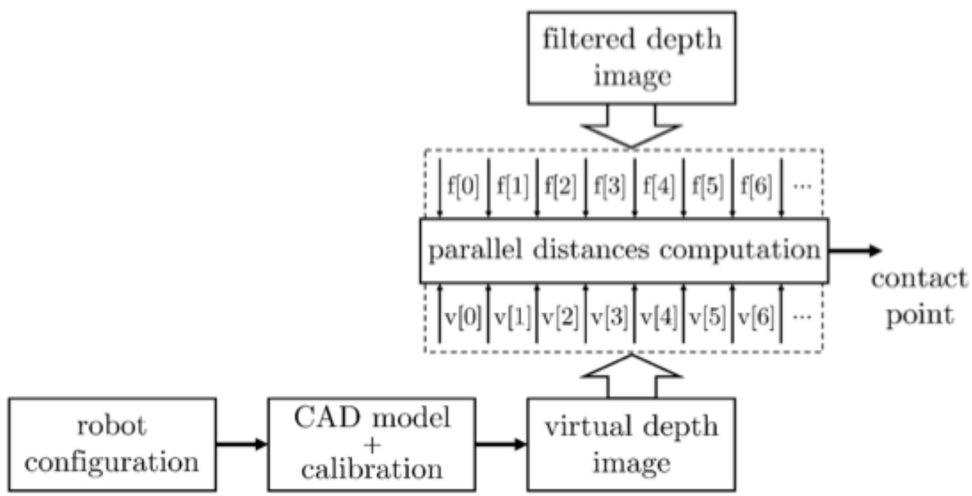
Contact point localization

Distance in depth space

- compute distances between all robot points $\boldsymbol{P}_D = \begin{pmatrix} p_{v,x} & p_{v,y} & d_v \end{pmatrix}^T$ in virtual depth image and all obstacles points $\boldsymbol{O}_D = \begin{pmatrix} p_{f,x} & p_{f,y} & d_f \end{pmatrix}^T$ in filtered depth image

$$d(\boldsymbol{O}, \boldsymbol{P}) = \sqrt{v_x^2 + v_y^2 + v_z^2}, \quad \text{with} \quad \begin{aligned} v_x &= \frac{(p_{f,x} - c_x)d_f - (p_{v,x} - c_x)d_v}{f\, s_x} \\ v_y &= \frac{(p_{f,y} - c_y)d_f - (p_{v,y} - c_y)d_v}{f\, s_y} \\ v_z &= d_f - d_v \end{aligned}$$

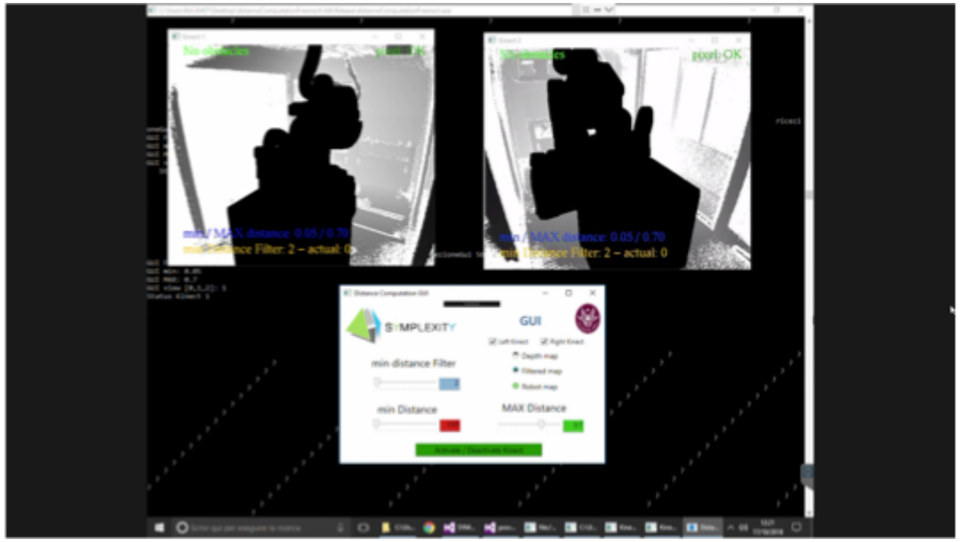
- when a contact is detected by the residual, the point of the visible robot surface at minimum distance from the obstacle is considered as contact point
- thanks to the parallel computing of the CUDA framework, the time needed to localize one or multiple contact points is the same



contact point localization processing

Safe coexistence in an industrial robotic cell

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



2 videos

depth images and GUI

- robot is moving at max 100 mm/s
- no safety zones were defined in ABB SafeMove
- Kinect **OK** (except when the view of one of the cameras is obstructed on purpose)

Force estimation for collaboration

Combining internal 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
  - use residual method to **detect** physical contact, **isolate** the colliding link, and **identify** the joint torques associated to the external contact force
  - use a depth sensor to **classify** the human parts in contact with the robot and **localize** the contact points 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

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

Force estimation

Some simplifying assumptions

- Dealing with contact forces
  - most **intentional** contacts with a single hand (or fingers) are **not** able to transfer relevant **torques**
  - to estimate reliably $\boldsymbol{\Gamma}_c$ we should have rank $\boldsymbol{J}_c = 6$, which is true only if the robot has $n \geq 6$ joints and the contact occurs at a link with index ≥ 6

assume ⇓ $\boldsymbol{M}_c = \boldsymbol{0}$

only a **pure Cartesian force** is considered

  - dimension of the task related to the contact force is $m = 6$ and its **estimation** is

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

  - the contact Jacobian can be evaluated once the contact point is detected by the external depth sensor closely monitoring the robot workspace

Force estimation

Some limitations of the residual method

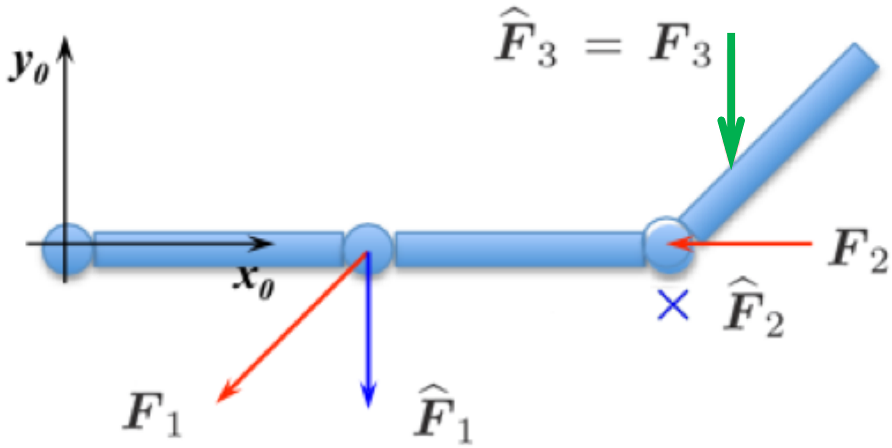
- **multiple** simultaneous contacts can be considered (e.g., with **both** human hands)

$$\begin{pmatrix} \widehat{\boldsymbol{F}}_1 \\ \widehat{\boldsymbol{F}}_2 \end{pmatrix} = \begin{pmatrix} \boldsymbol{J}_{L1}^T(\boldsymbol{q}) & \boldsymbol{J}_{L2}^T(\boldsymbol{q}) \end{pmatrix}^{\#} \boldsymbol{r}$$

  but with much less confidence in the resulting force estimates (detection is instead ok)

- **estimates** will be limited to only those components of $\boldsymbol{F}_c$ that can be detected by the residual

- all **forces** $\boldsymbol{F}_c \in \mathcal{N}(\boldsymbol{J}_c^T(\boldsymbol{q}))$ will never be recovered ↔ they are absorbed by the robot structure



- Evaluation of estimated contact force

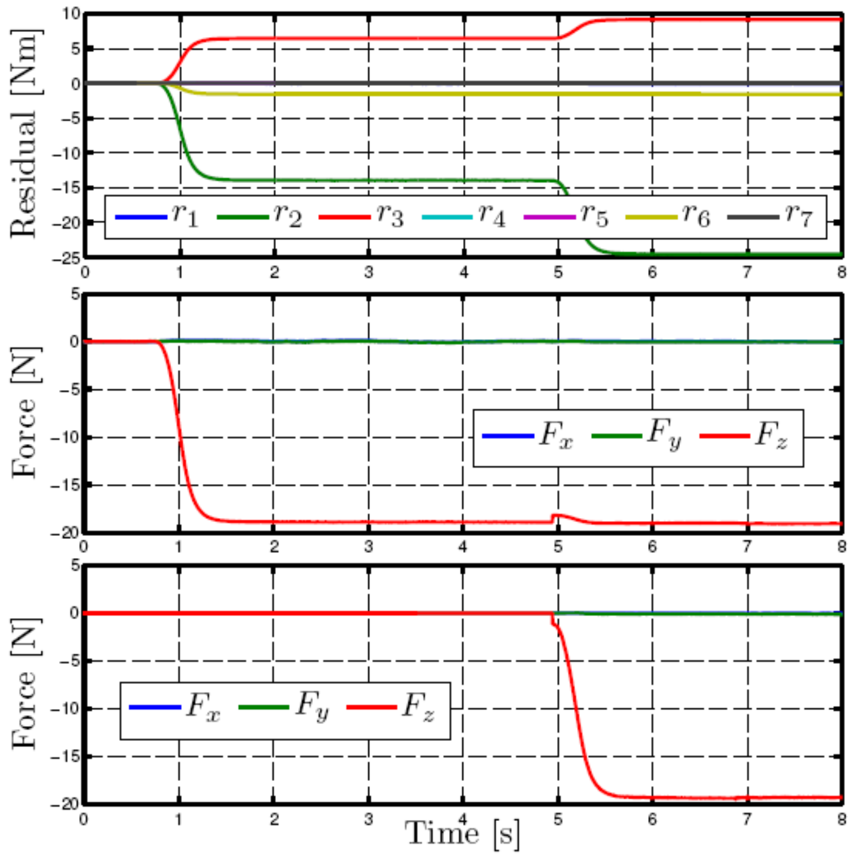
$$\widehat{\boldsymbol{F}}_c = \left(\boldsymbol{J}_c^T(\boldsymbol{q})\right)^{\#} \boldsymbol{r}$$

  - estimation accuracy was initially tested using known masses in known positions
  - a single mass hung either on link 4 or on link 7, to emulate a **single** (point-wise) contact

			using $\boldsymbol{J}_{Lc}$		using $\boldsymbol{J}_c$	
Link #	Mass	F_z	$\widehat{F}_z$	Deviation	$\widehat{F}_z$	Deviation
4	1.93	-18.93	-18.75	0.95%	-4.46	76.43%
7	1.93	-18.93	-18.91	0.1%	-18.82	0.58%

  - a mass hung on link 7, and then a second on link 4 so as to emulate a **double** contact

Link #	Mass	F_z	$\widehat{F}_z$	Deviation
4	2.03	-19.91	-19.43	2.41%
7	1.93	-18.93	-19.04	0.58%



case of two masses

More validation of the virtual force sensor

In static and dynamic conditions, using a hand-held F/T sensor (February 2019)

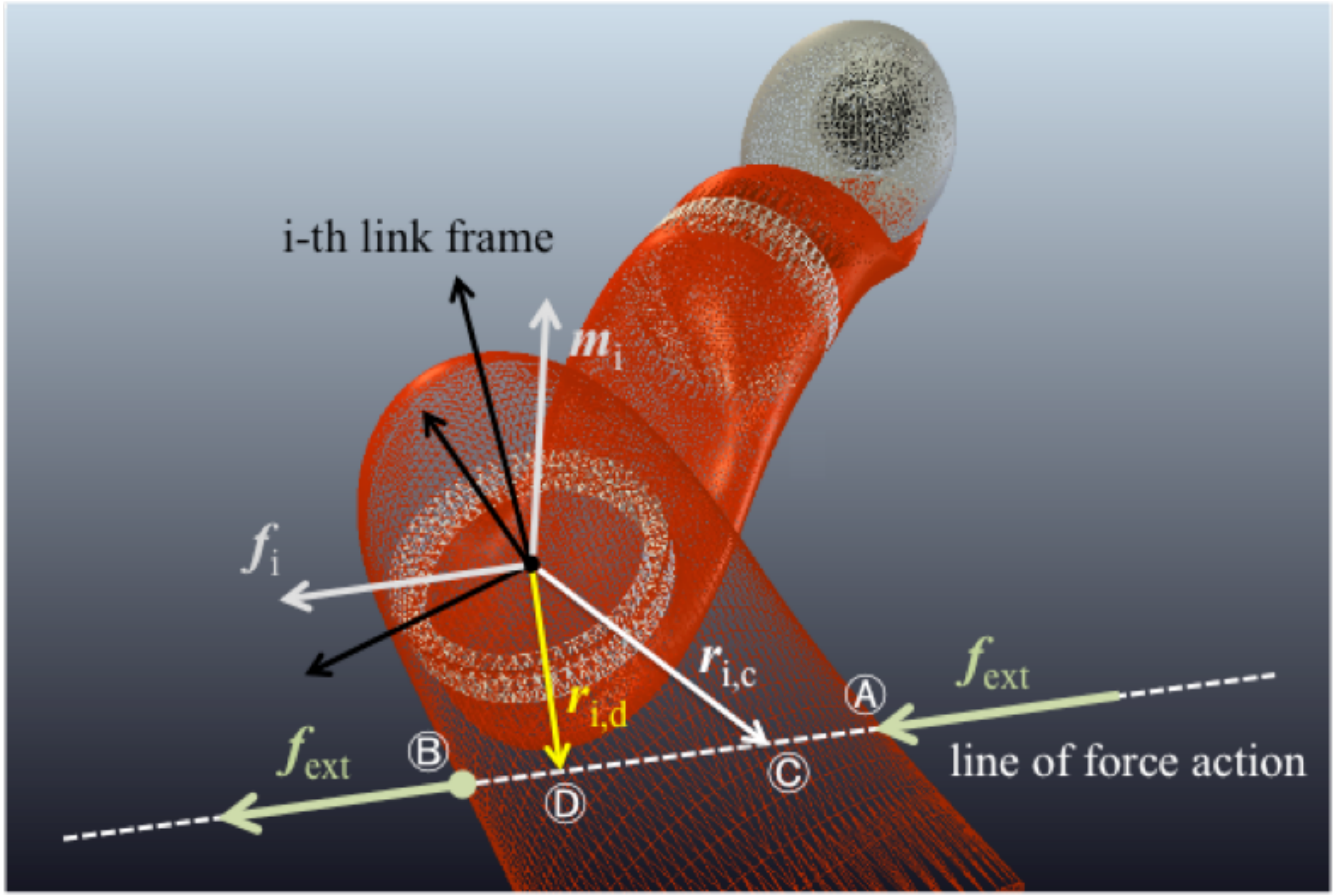
- comparing the F/T ground truth contact force measure with its residual-based estimation
  - with robot at rest (pushing)
  - in robot motion (hitting)

2 videos

Estimation of the contact force

Sometimes, even without external sensing

- if contact is sufficiently “down” the kinematic chain (**≥ 6 residuals** are available), the estimation of pure contact forces does not need any external information ...



Control based on contact force estimation

Used within an admittance control scheme (IROS 2014)

https://youtu.be/Yc5FoRGJsrc

video

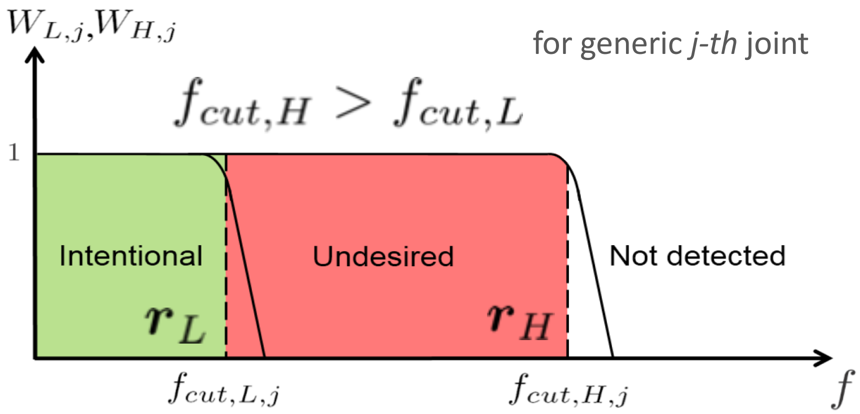
Collision or collaboration?

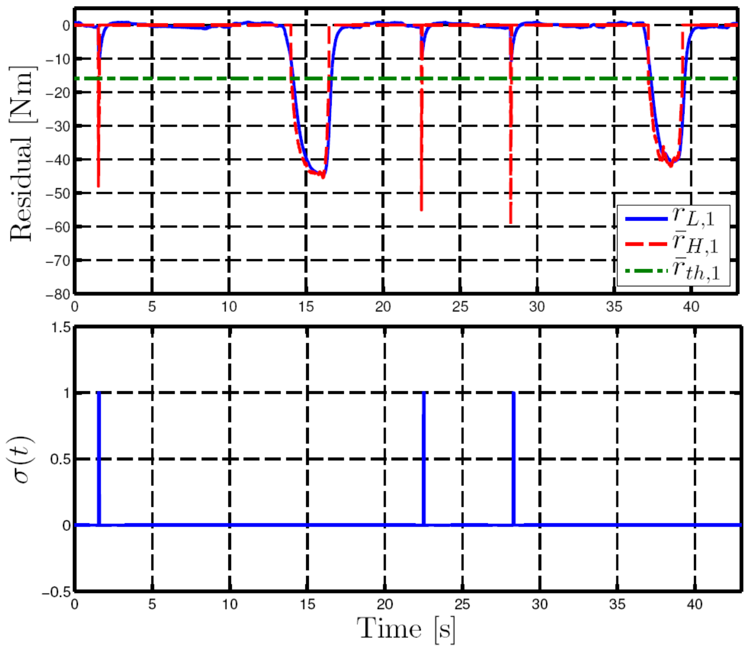
Distinguishing hard/accidental collisions and soft/intentional contacts

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

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

- a threshold is added to prevent false collision detection during robot motion





video

Collaboration control

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

- shaping the robot dynamic behavior in specific **collaborative tasks**
  - 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)
    - **impedance, force** or **hybrid force-motion** control laws (needs **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

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

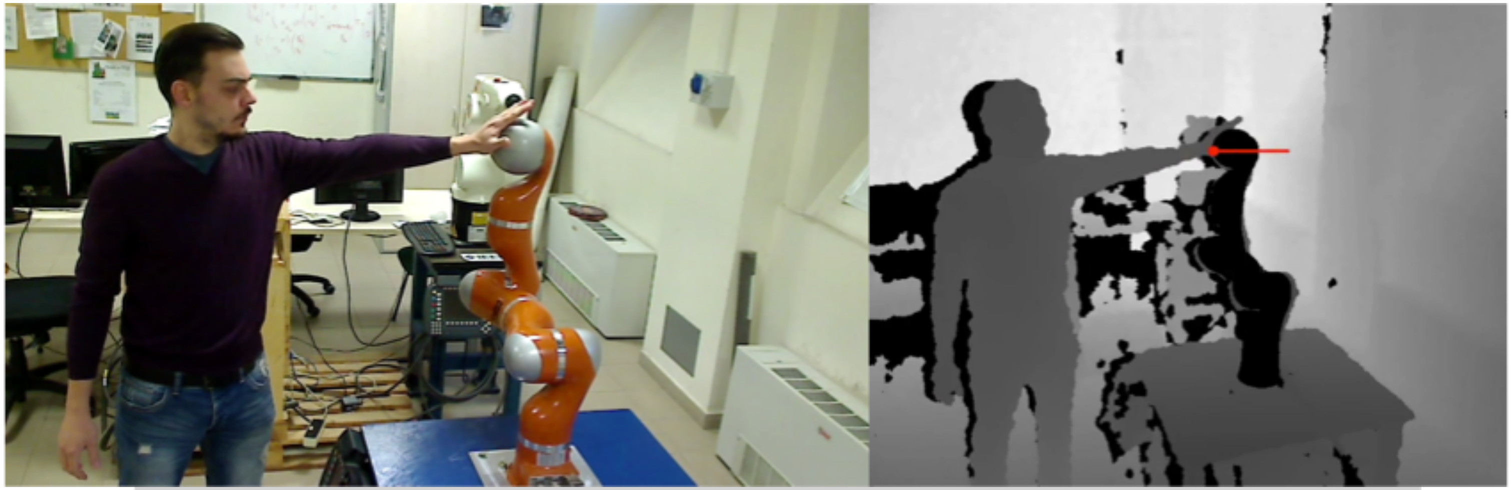
$$\boldsymbol{F}_a = \widehat{\boldsymbol{F}}_c + \boldsymbol{K}_p(\boldsymbol{p}_d - \boldsymbol{p}_c), \qquad \boldsymbol{K}_p = k_p \boldsymbol{I} > 0$$

↖ initial contact point position when interaction begins

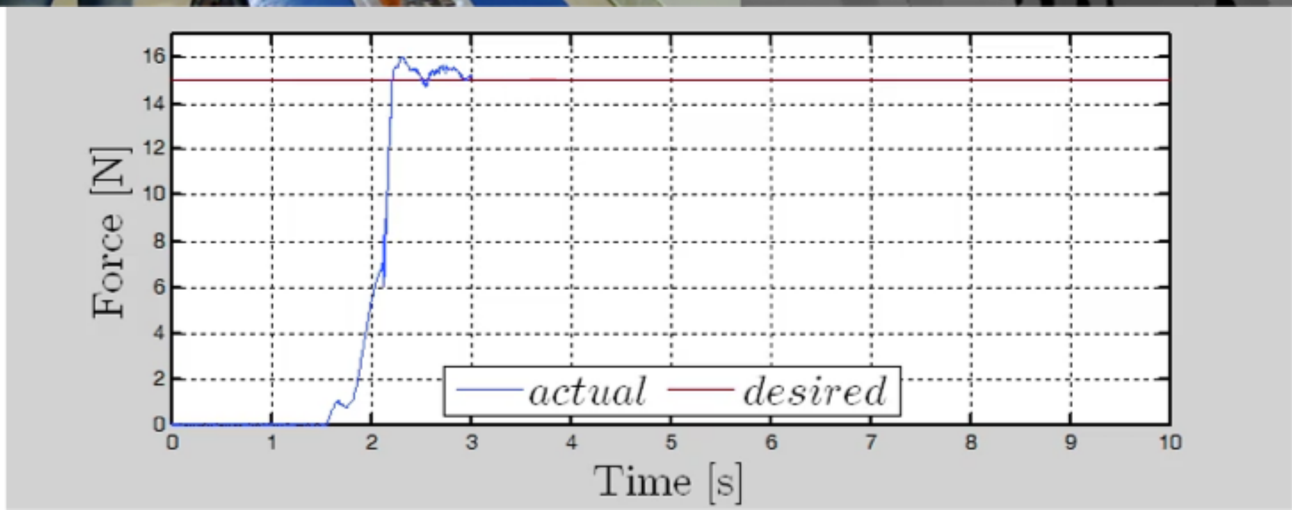
Contact force regulation with virtual force sensing

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

- contact force estimation & control (anywhere/anytime)



video

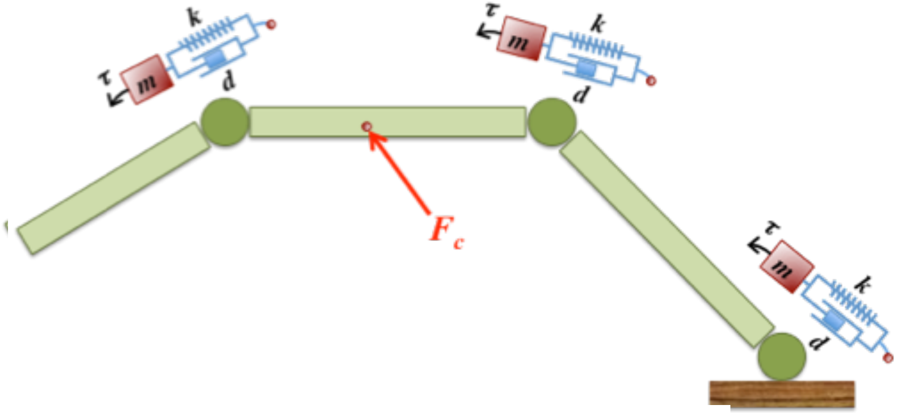


see **ICRA 2015 trailer** (at 3’26’’):
https://youtu.be/glNHq7MpCG8 (Italian); https://youtu.be/OM_1F33fcWk (English)

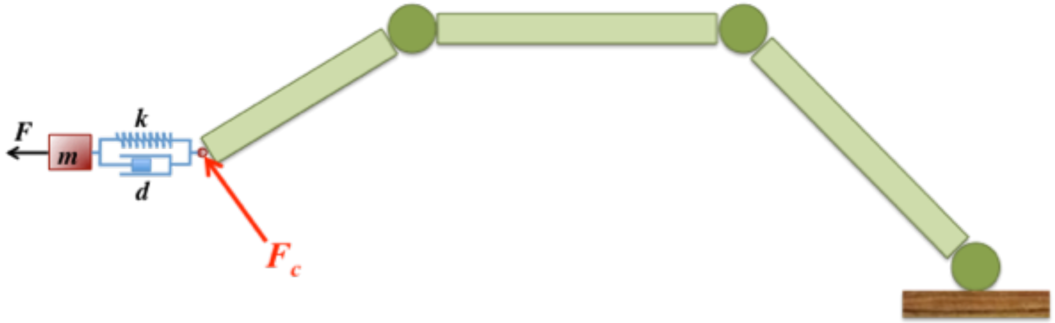
Impedance-based control of interaction

Reaction to contact forces by generalized impedance —at different levels

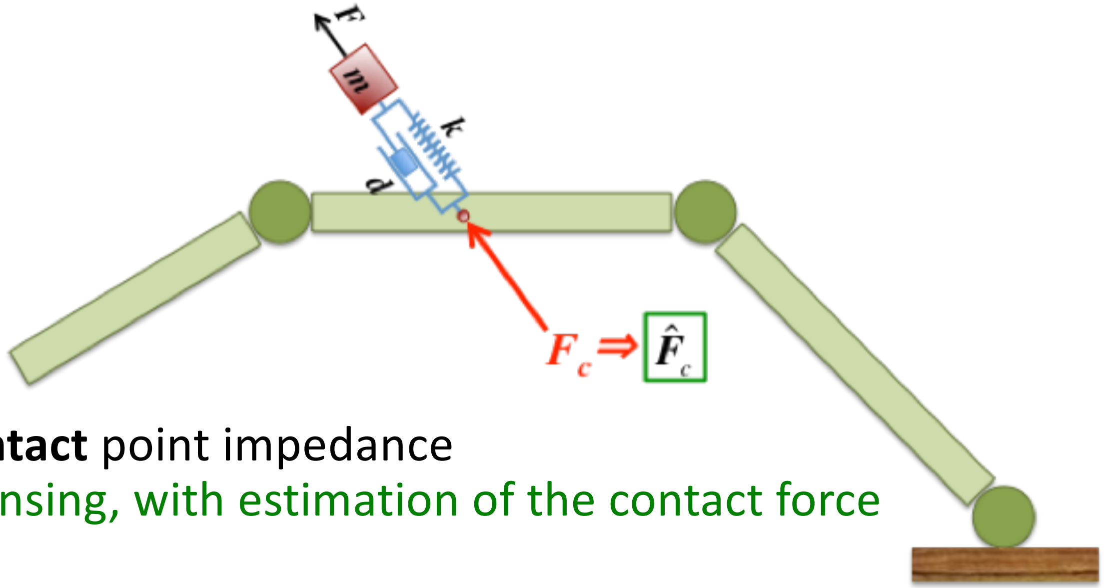
consider a fully rigid robot



Joint impedance
needs joint torque sensors



Cartesian impedance
needs F/T sensor



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

Control of generalized impedance

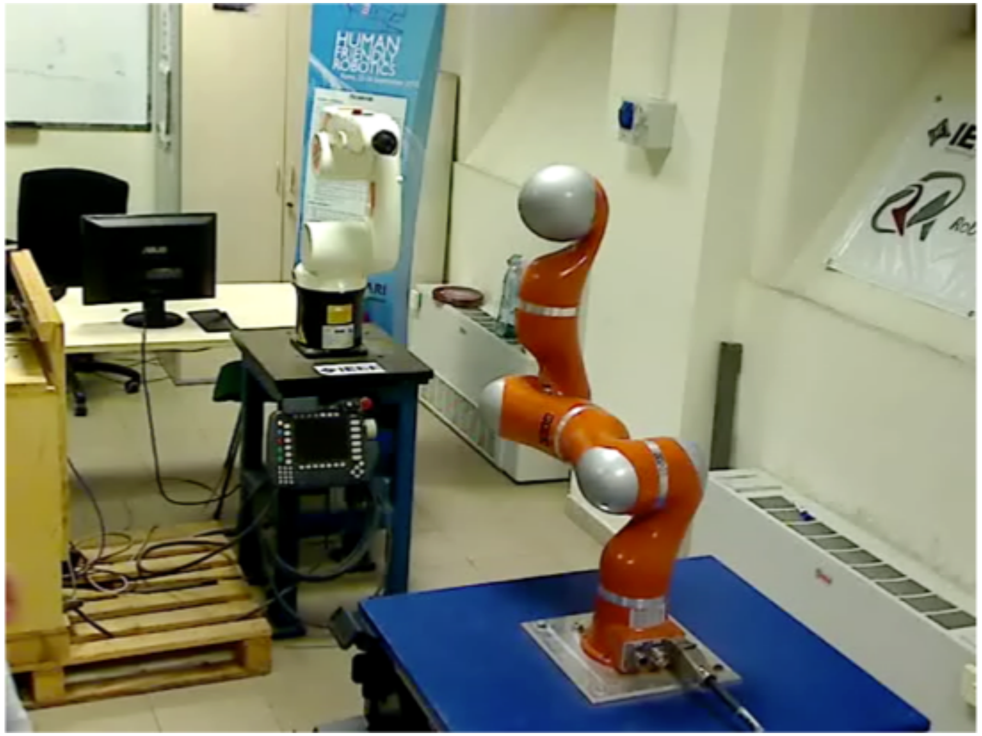
HR collaboration at the contact level (ICRA 2015)

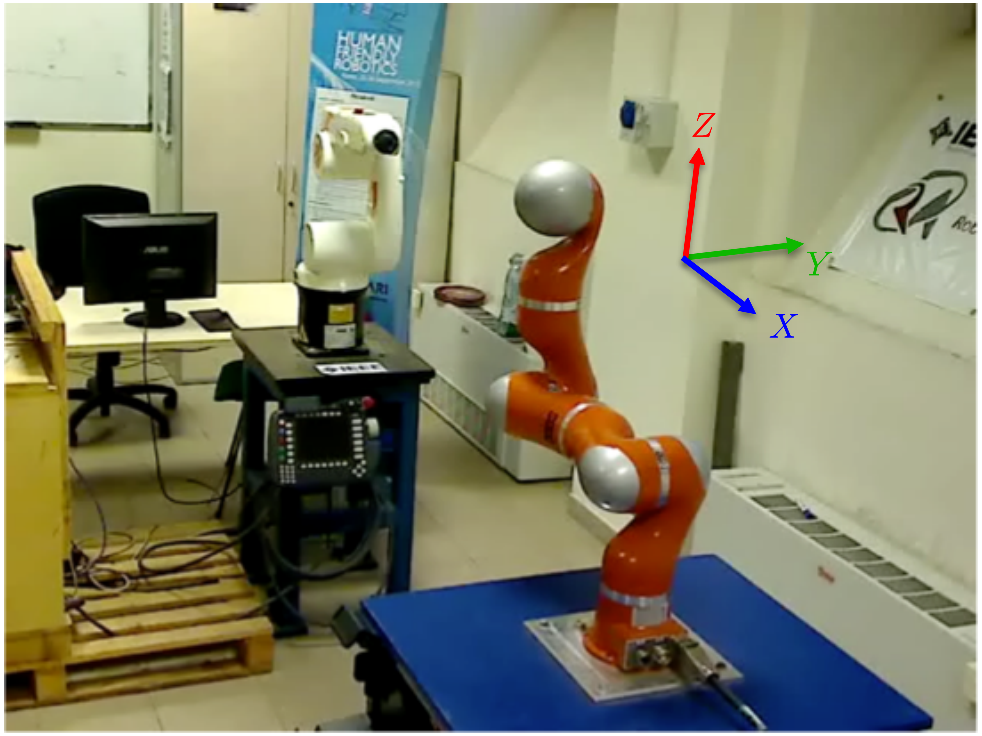
https://youtu.be/NHn2cwSyCCo for these 2 videos (and the next two)

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])

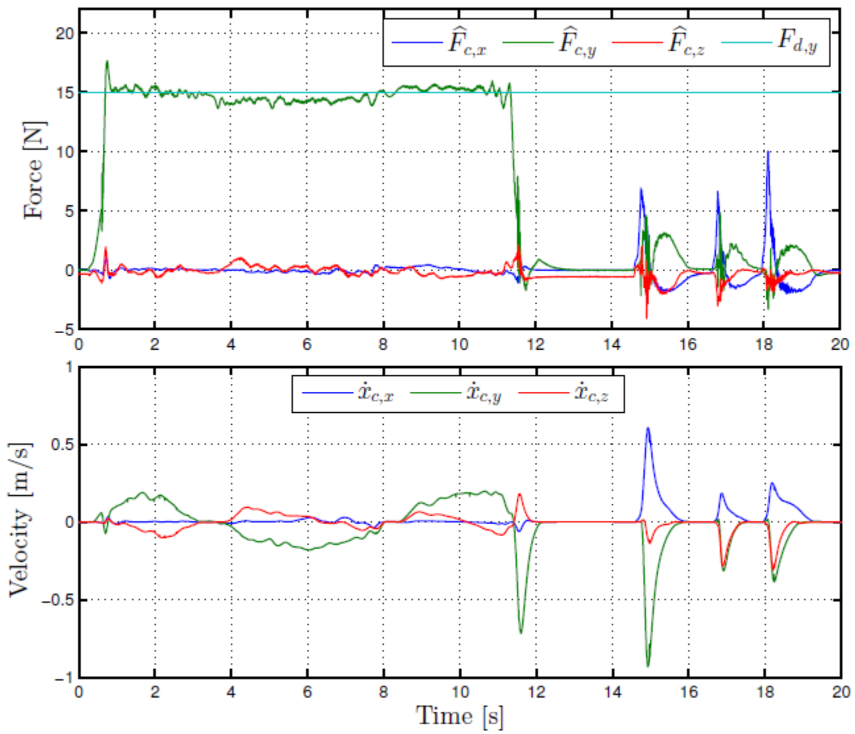
Control of generalized contact force

Direct force scheme

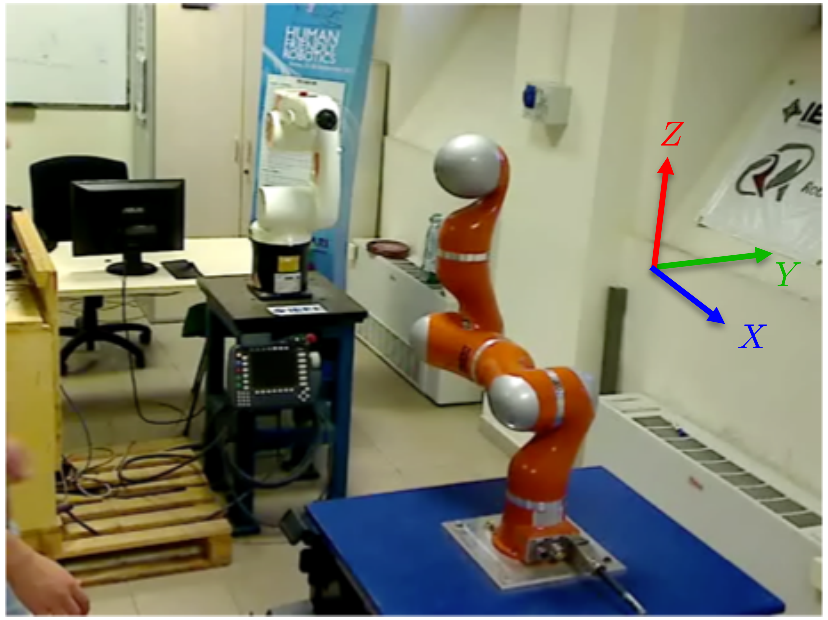
- explicit **regulation** of the **contact force** to a desired value, by imposing

$$\boldsymbol{M}_d \ddot{\boldsymbol{x}}_c + \boldsymbol{K}_d \dot{\boldsymbol{x}}_c = \boldsymbol{K}_f (\boldsymbol{F}_d - \widehat{\boldsymbol{F}}_c) = \boldsymbol{K}_f \boldsymbol{e}_f$$

- a force control law needs always a measure (here, an **estimate**) of contact force
- **task-compatibility**: human-robot contact direction vs. desired contact force vector



$$F_{d,x} = 0, \quad F_{d,y} = 15N, \quad F_{d,z} = 0$$



video

however, *drift effects* due to poor control design

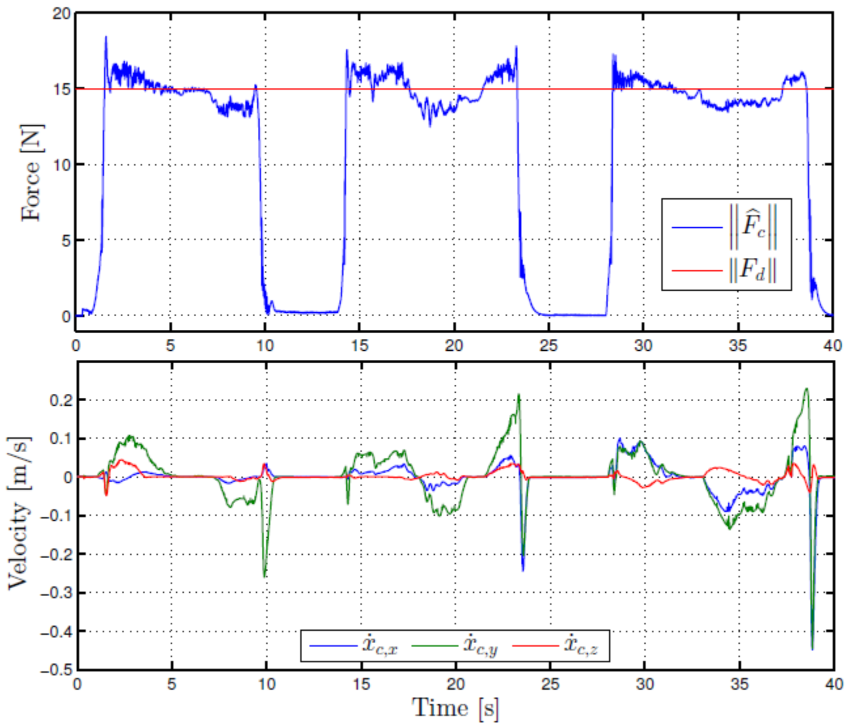
Control of generalized contact force

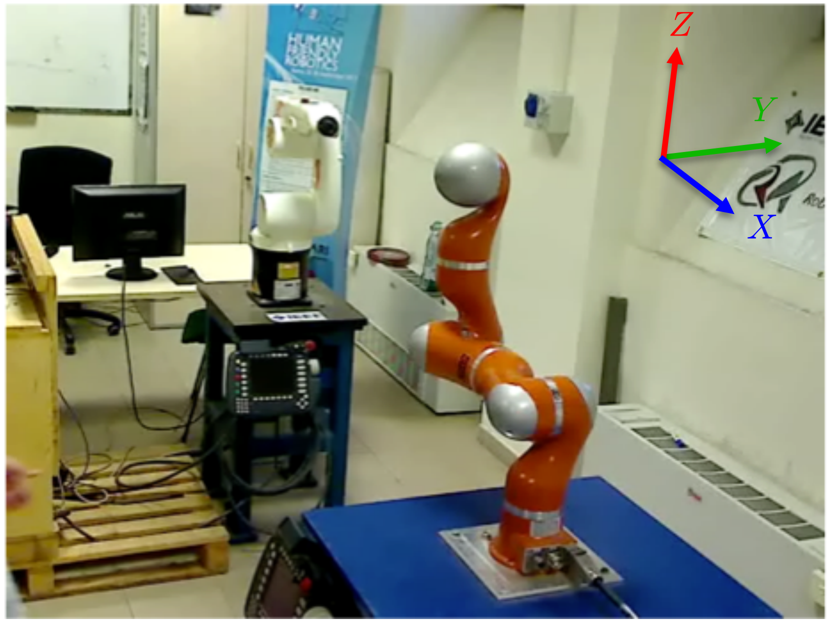
Task-compatible force control scheme (ICRA 2015)

- only the **norm** of the desired contact force is controlled along the instantaneous **direction** of the estimated contact force

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

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





video

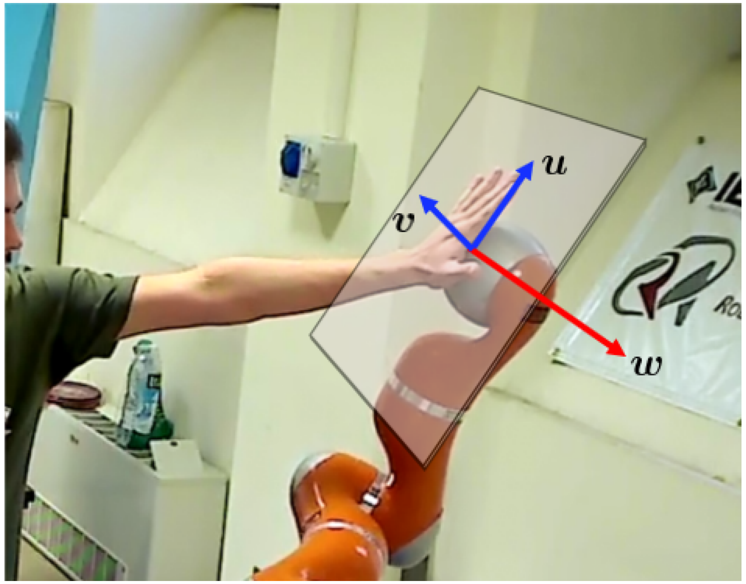
task-compatible control of contact force

Collaboration control

Hybrid force/velocity control scheme (ICRA 2016)

- it allows to control both contact force and motion in **two** mutually independent sub-spaces
- extends at the contact level a hybrid force/velocity control law, with the orientation of **contact task frame** being determined instantaneously
- task frame obtained by a rotation matrix $\boldsymbol{R}_t$ such that $\boldsymbol{z}_t$ is aligned with the **estimated** contact force

$$\boldsymbol{R}_t = \begin{bmatrix} \boldsymbol{u} & \boldsymbol{v} & \boldsymbol{w} \end{bmatrix} = \left[\begin{array}{ccc} \boldsymbol{u} & \boldsymbol{v} & \dfrac{\widehat{\boldsymbol{F}}_c}{\|\widehat{\boldsymbol{F}}_c\|}, \end{array} \right]$$



- the auxiliary command is given by

$$\boldsymbol{a} = \boldsymbol{J}_c^{\#} \boldsymbol{M}_d^{-1} (\boldsymbol{R}_t \boldsymbol{a}_c + \boldsymbol{M}_d (\dot{\boldsymbol{R}}_t {}^t\dot{\boldsymbol{x}}_c - \dot{\boldsymbol{J}}_c \dot{\boldsymbol{q}})) + \boldsymbol{P}_c \ddot{\boldsymbol{q}}_0$$

- **complete decoupling** between force control and velocity control can be achieved by choosing the new auxiliary control input as

$$\boldsymbol{a}_c = \boldsymbol{S}_f^c \, \ddot{y}_f + \boldsymbol{S}_\nu^c \, \dot{\boldsymbol{\nu}}$$

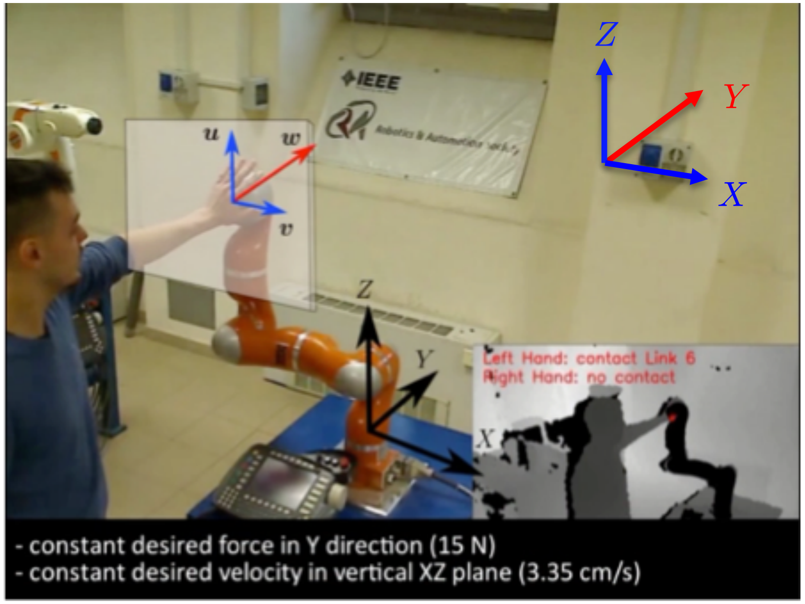
Collaboration control

Hybrid force/velocity control at contact level (IROS 2016)

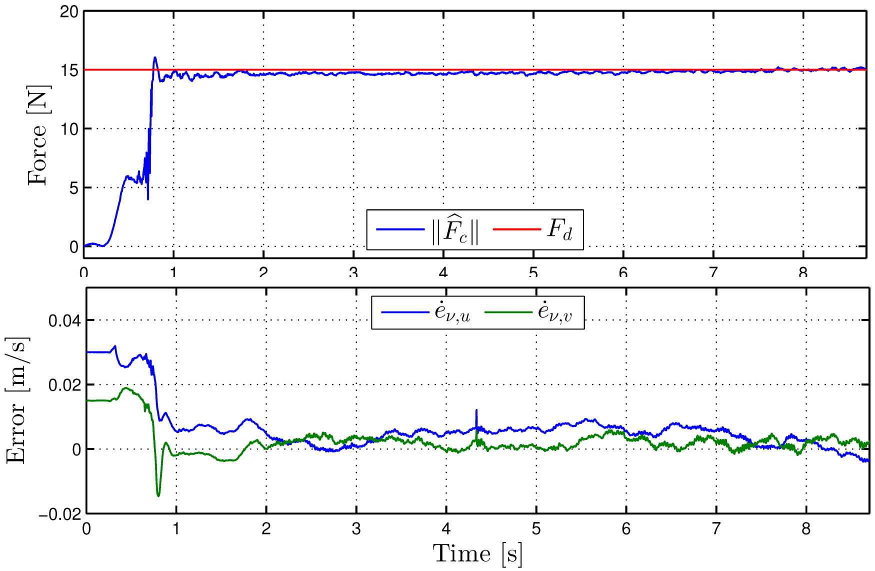
https://youtu.be/tIhEK5f00QU

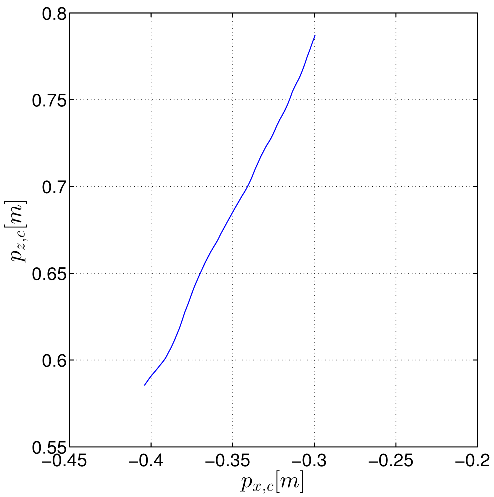
- desired contact force along Y direction regulated to $\boldsymbol{F}_d = 15[N]$
- constant desired velocity to perform a line in the vertical XZ plane

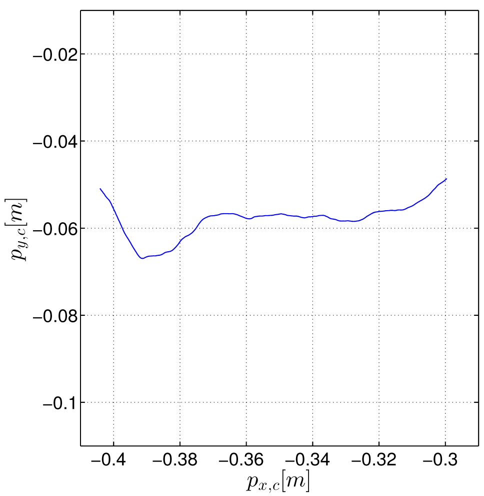
$$\boldsymbol{\nu}_d = \begin{bmatrix} 0.015 \\ 0.03 \end{bmatrix} \qquad \dot{\boldsymbol{\nu}}_d = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$



video







Validation of collaboration control with a F/T sensor

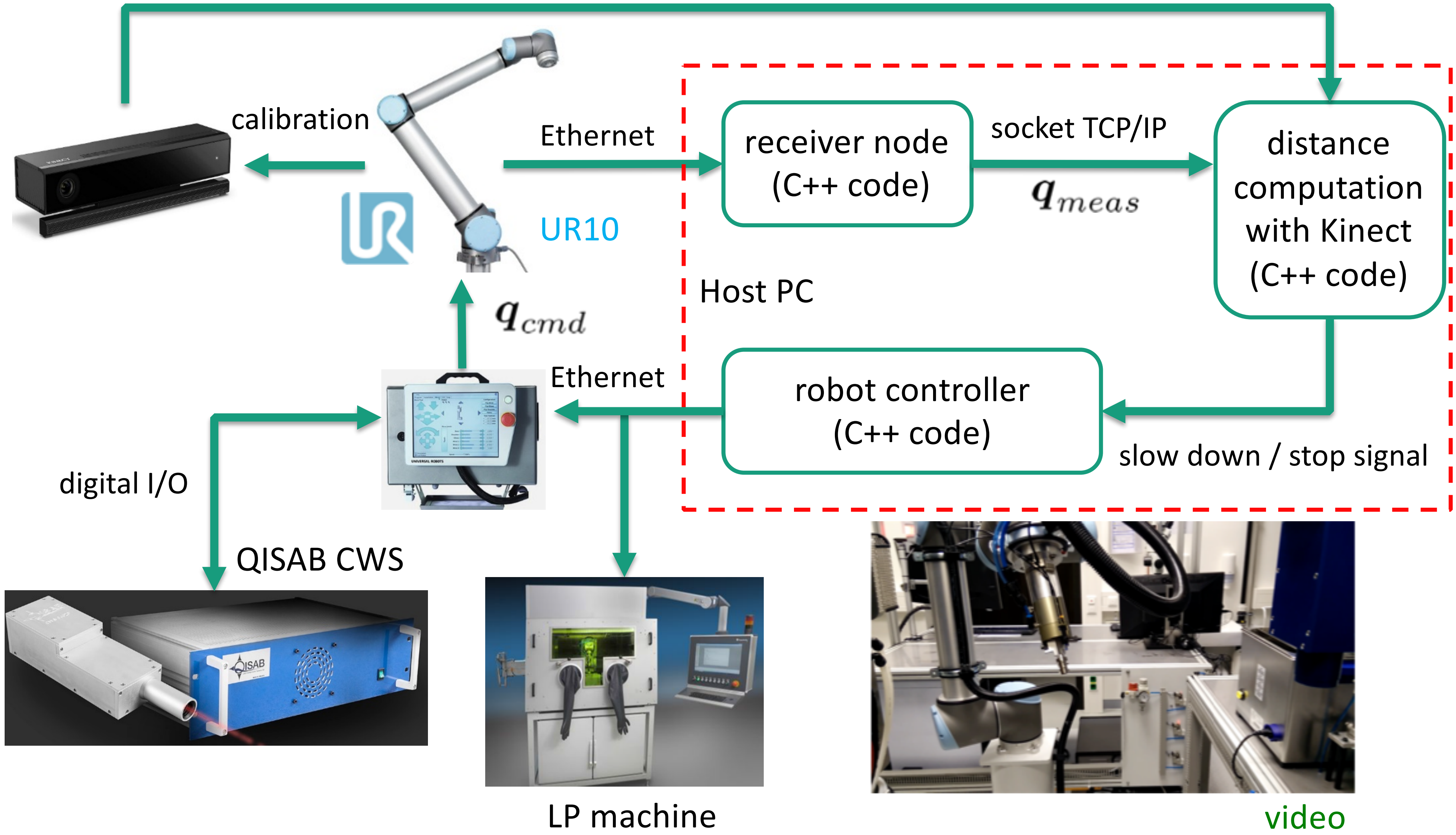
Force and hybrid force/velocity control schemes at contact level (February 2019)

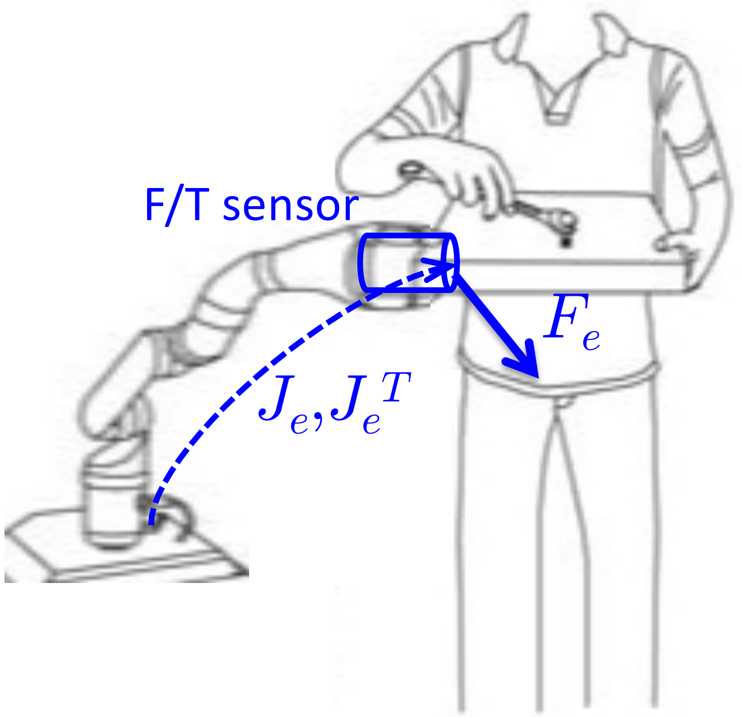
- desired contact force along the estimated contact direction regulated at 15 N
- … and trajectory control with constant speed along a circle in the orthogonal plane

2 videos

Scenario for HRC in manual polishing

EU H2020 SYMPLEXITY project: Preparing a metallic part for a laser polishing machine



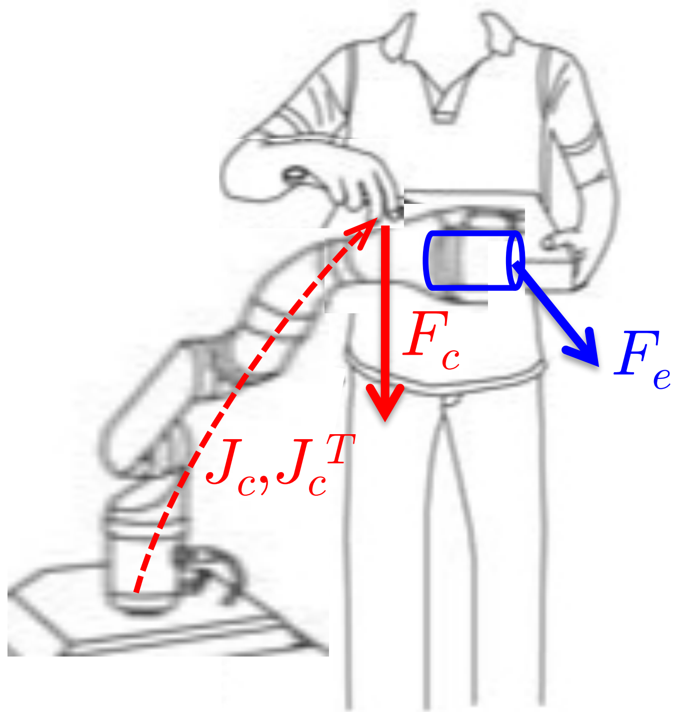


Force/Torque (F/T) sensor at wrist

- manual polishing force is **measured**
- end-effector Jacobian is **known**

contact force at unknown location

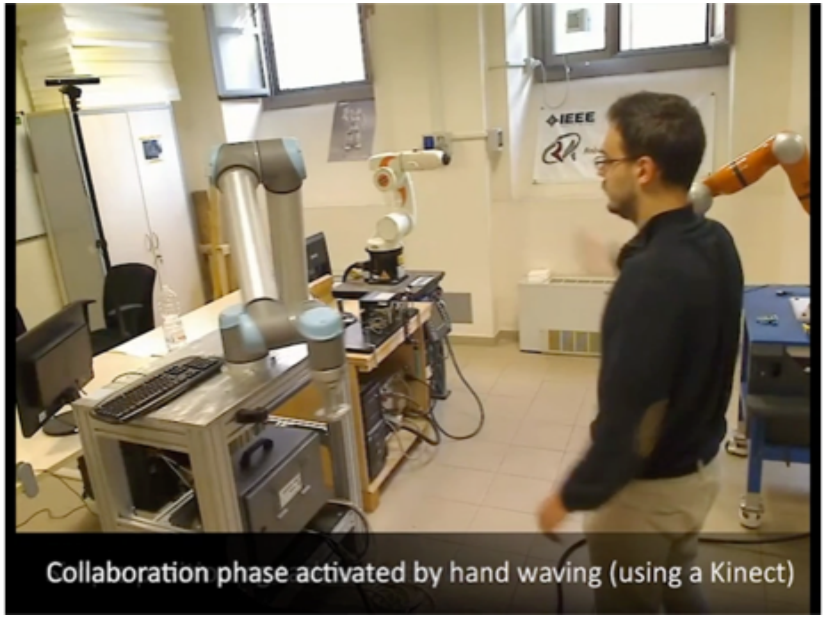
- **not** measurable by the F/T sensor
- possibly applied by the human **while** manipulating the work piece held by robot
- contact Jacobian is **not** known



HRC phase with UR10 robot

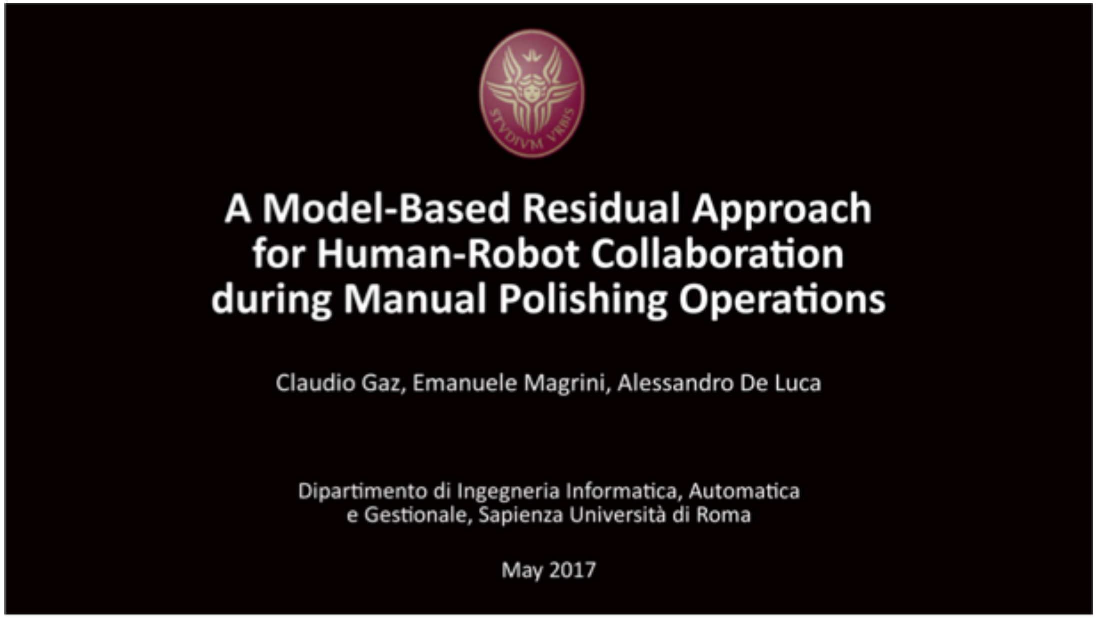
Experimental results (Mechatronics 2018)

https://youtu.be/slwUiRT_IJQ



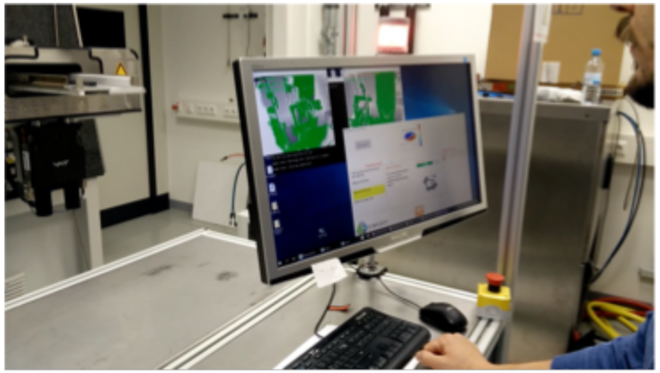
no F/T sensor, switching to FreeDrive mode

https://youtu.be/bjZbmlAclYk



with F/T sensor, using our residual method

part to be polished

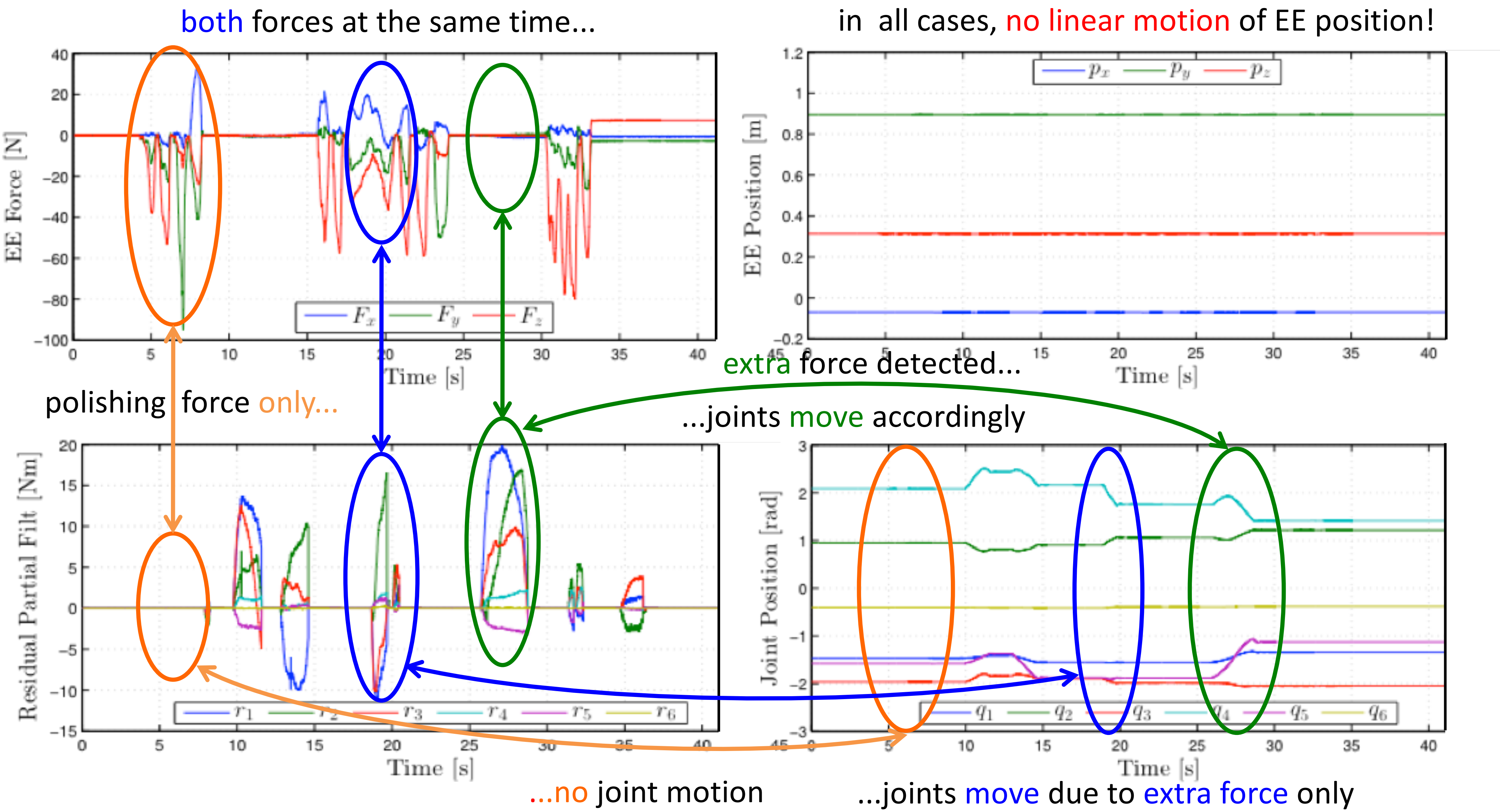


3 videos

for a similar behavior wth the KUKA LWR
see https://youtu.be/TZ6nPqLPDxI

HRC phase with UR10 robot

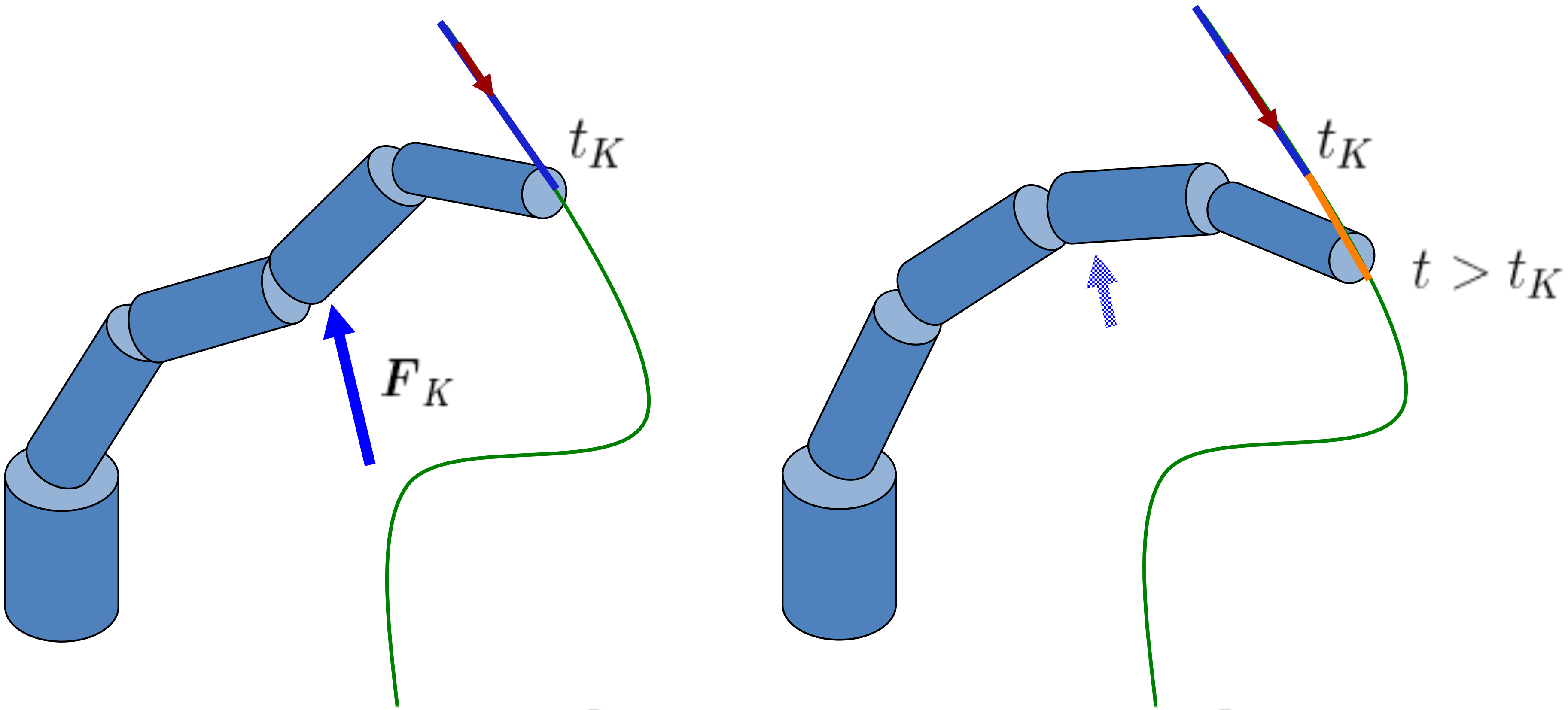
Experimental results (separating F/T measures from the residuals)



Use of kinematic redundancy in pHRI

Robot reaction to collisions, in parallel with execution of original task

- collision detection ⇒ robot reacts so as to preserve as much as possible (if at all possible) the execution of a planned task trajectory, e.g., for the end-effector

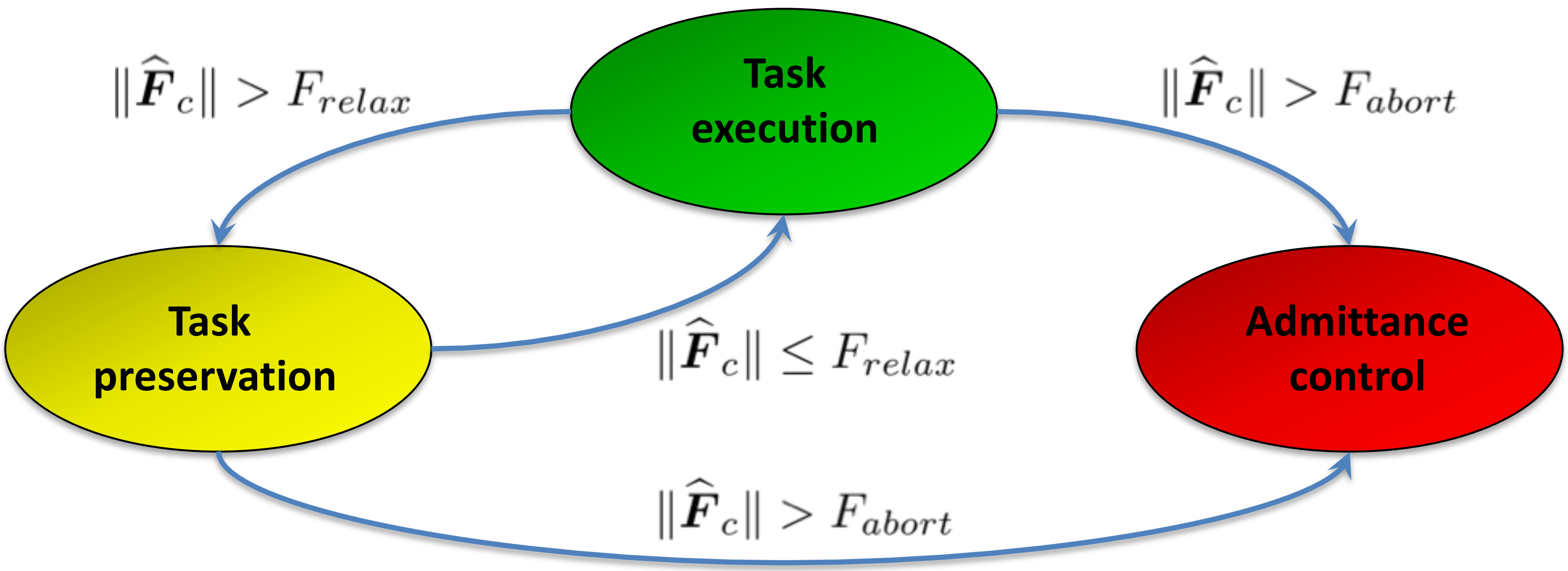


$$\tau = M(q)G(q)\left[\ddot{x} - \dot{J}(q)\dot{q} + J(q)M^{-1}(q)n(q,\dot{q})\right] + M(q)(I - G(q)J(q))M^{-1}(q)\tau_0.$$

Selective reaction to estimated contact force

Robot control strategy (IROS 2008, IROS 2017)

- the control scheme **exploits robot redundancy** in order to follow a Cartesian trajectory, despite the possible occurrence of accidental collisions on the robot body
- execution of the original end-effector motion task is preserved while reacting to a detected contact, with the **estimated contact force** above a threshold F_{relax} but **not too large**
- using null-space motion, the robot tries to **eliminate, reduce** or **keep low** the contact force
- if the contact force exceeds a threshold F_{abort}, the robot abandons the original task and reacts by imposing **admittance control at the contact**



Use of kinematic redundancy

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

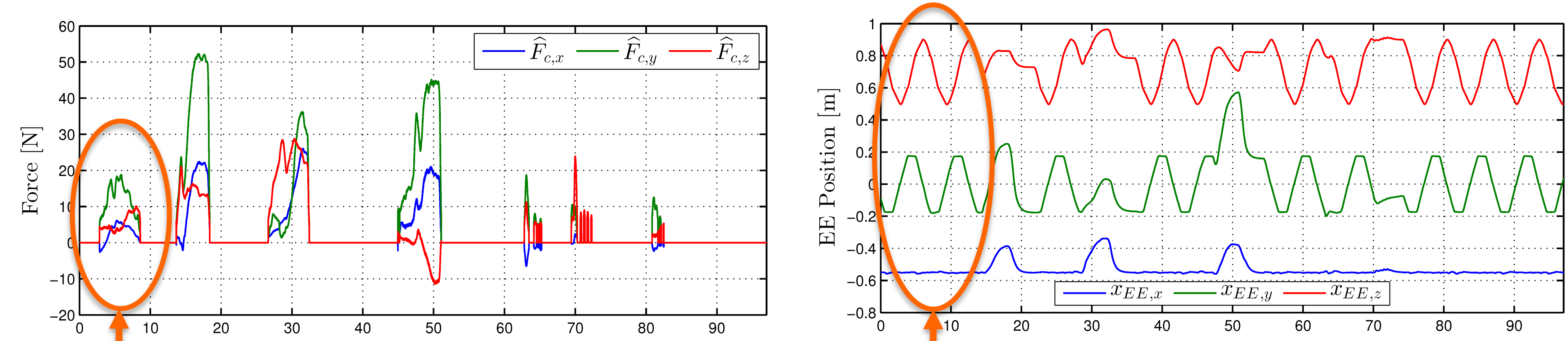
https://youtu.be/q4PZKE-kgc0 video

idle ⇔ relax ⇔ abort

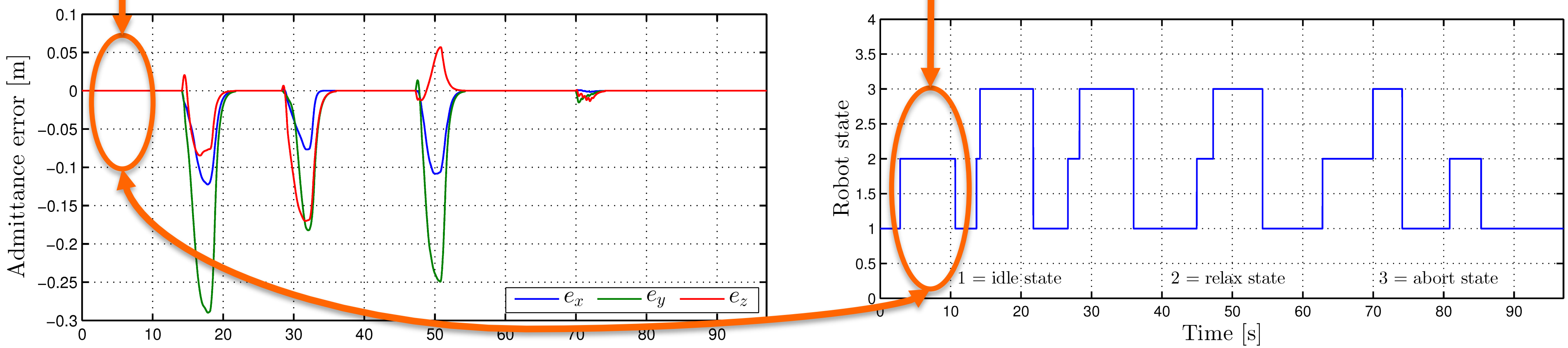
pHRI experiments

Analysis of results

...and **no** task perturbation



estimated force: $F_{relax} < \|\widehat{\boldsymbol{F}}_c\| \leq F_{abort}$

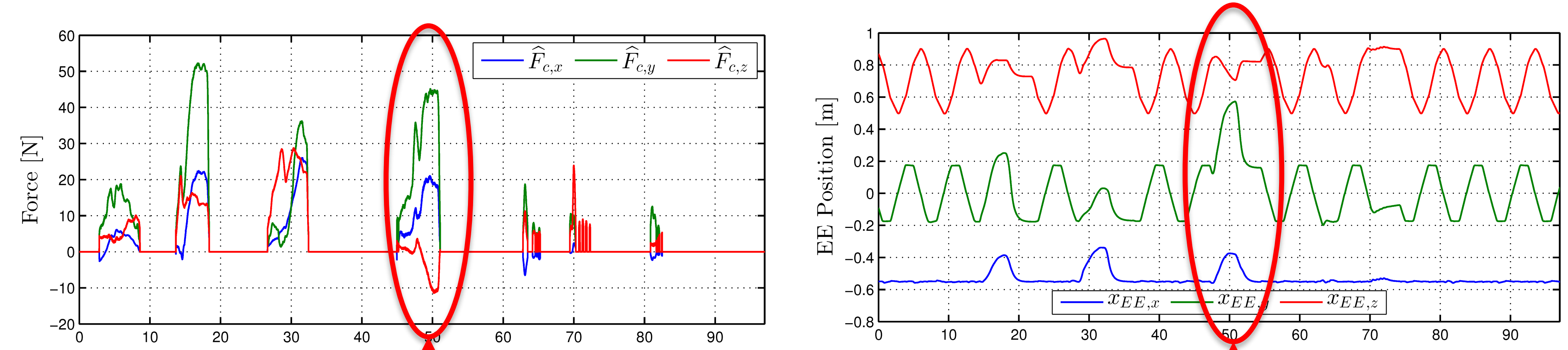


robot in **relax** state, no admittance error...

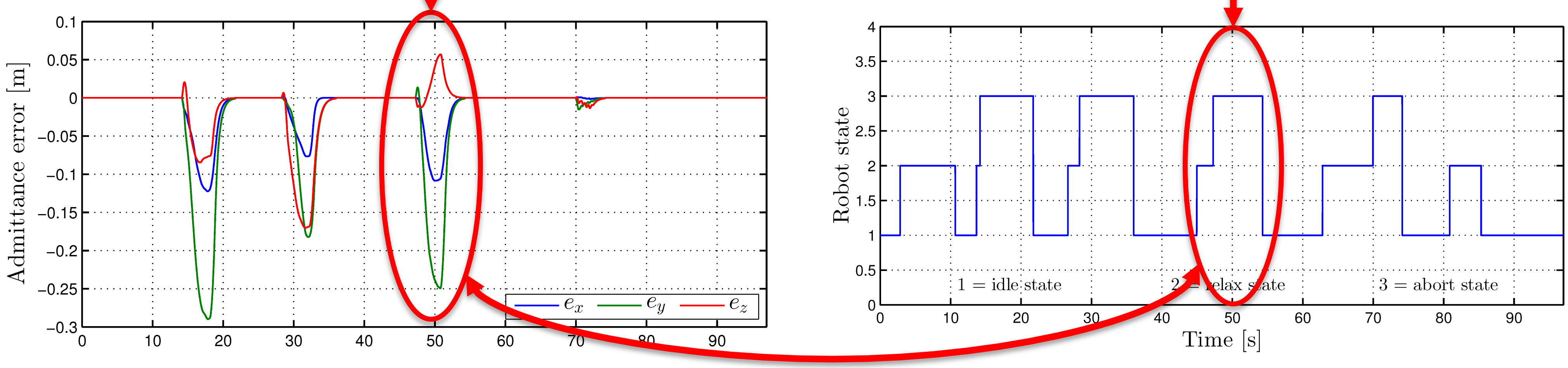
pHRI experiments

Analysis of results

…and the original task is **abandoned**



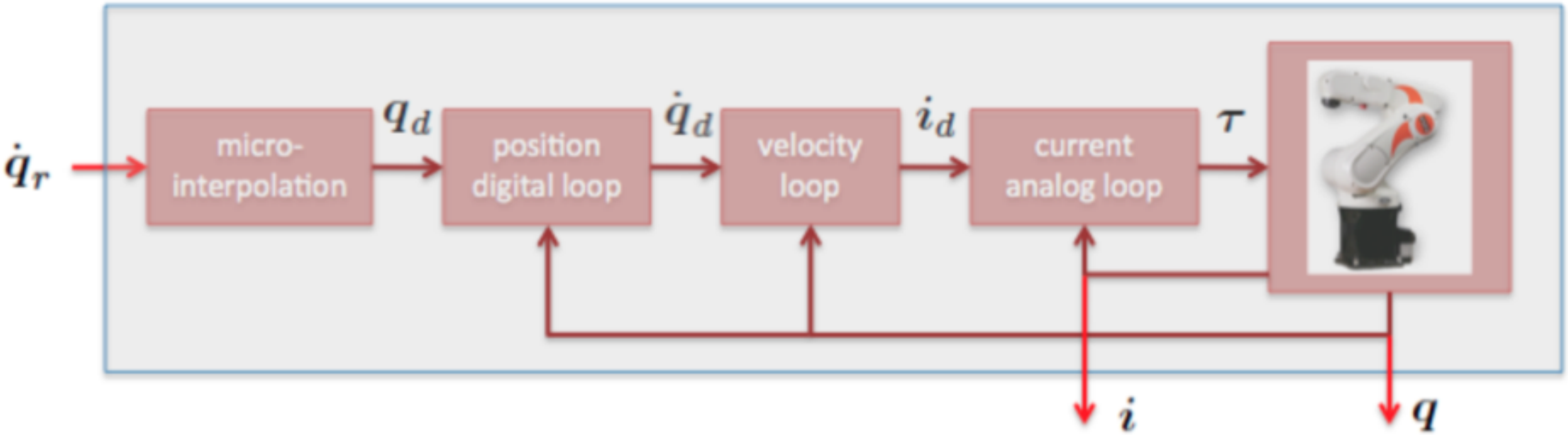
estimated force: $\|\widehat{\boldsymbol{F}}_c\| > F_{abort}$



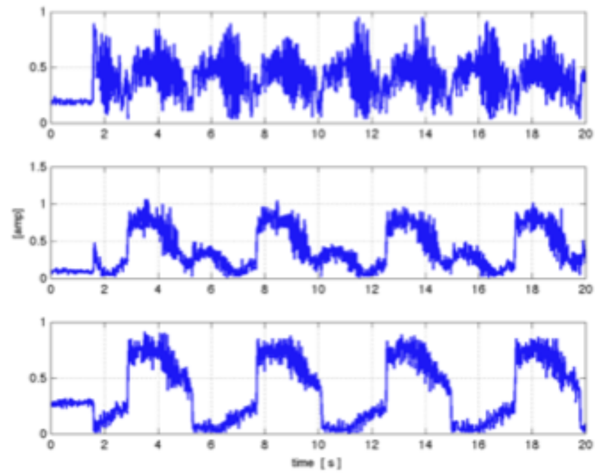
the robot goes in **abort** state, an admittance error is present…

HRC under a closed control architecture

KUKA KR5 Sixx R650 robot



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

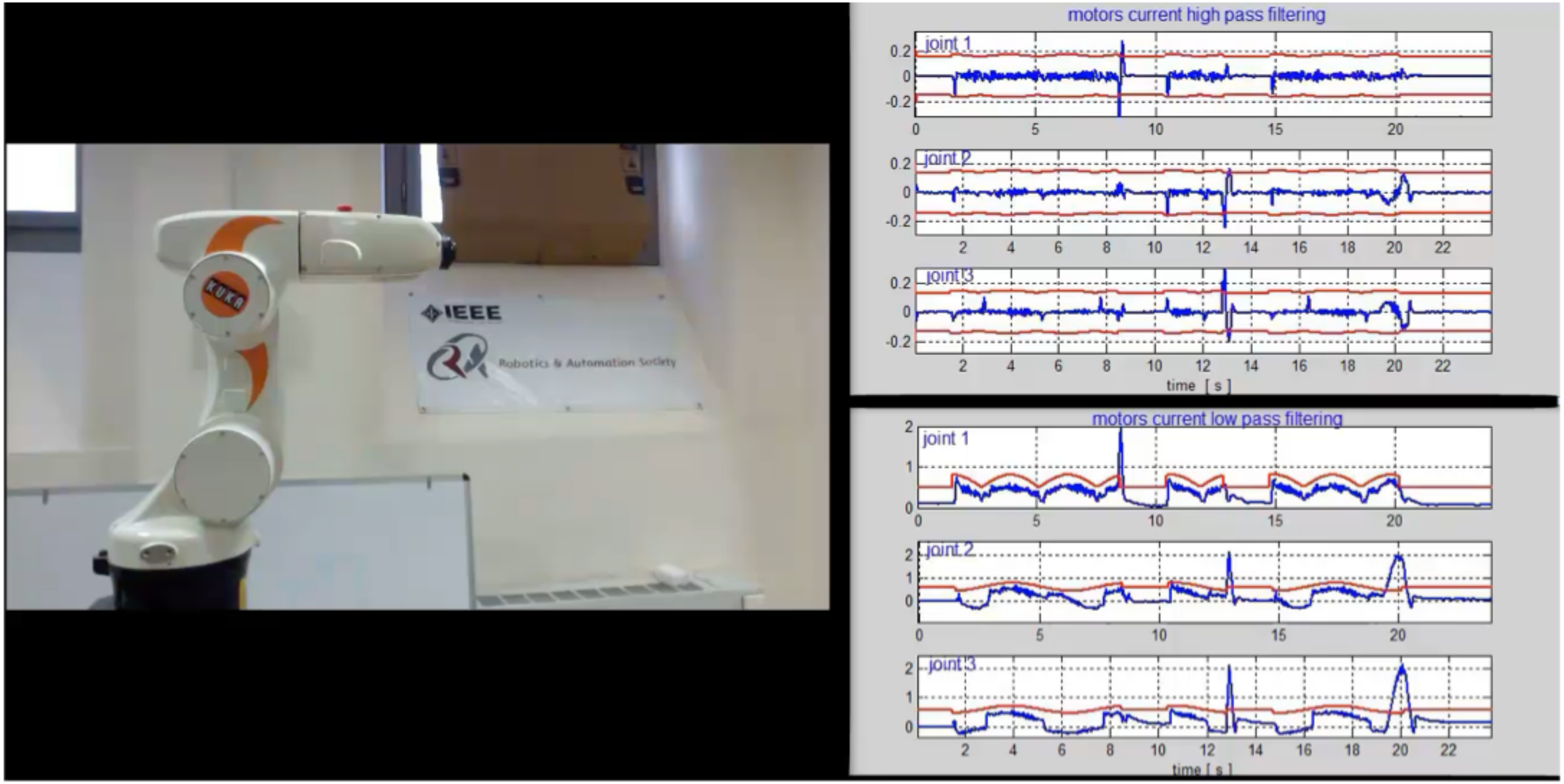


typical motor currents on first three joints

Distinguish accidental collisions from intentional contacts

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

video

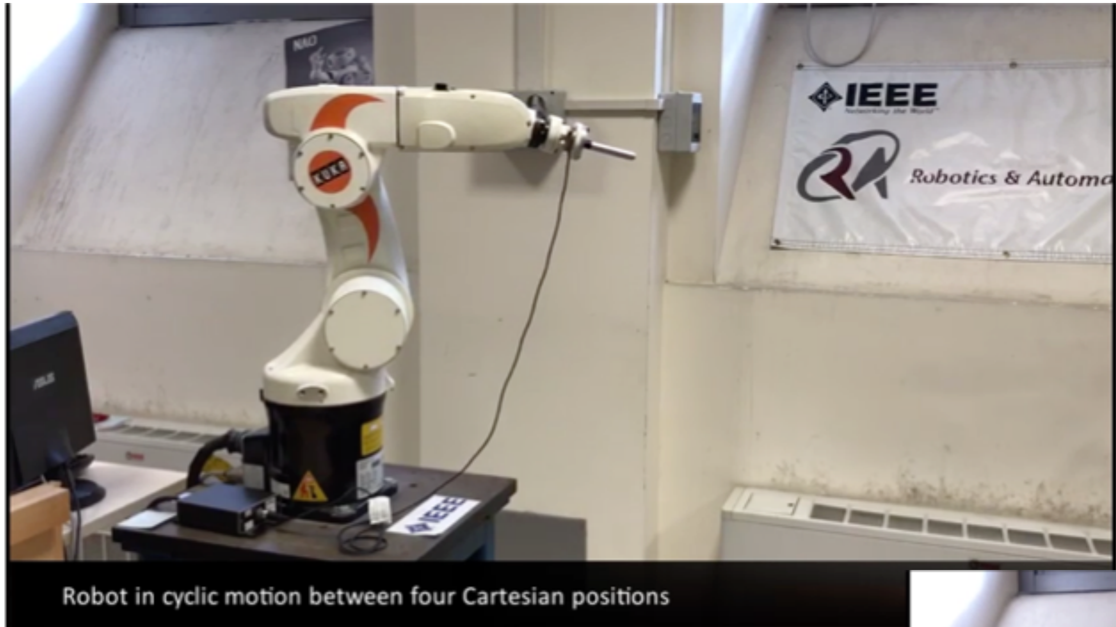


using high-pass and low-pass filtering of motor currents

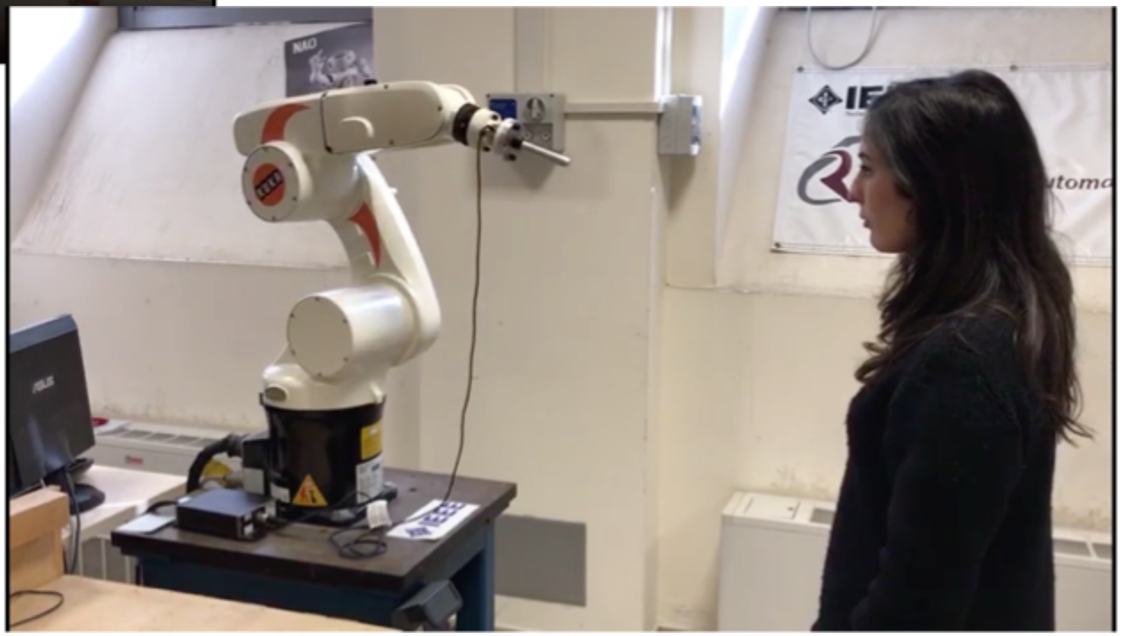
— here collaboration mode is manual guidance of the robot

Combining motor currents and F/T sensor data

Enhanced flexible interaction by filtering, thresholding, merging signals (ICRA 2019)



2 videos



interaction may occur
at the **end-effector**,
on robot **body**, or **both**

Conclusions

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

- framework for safe human-robot coexistence and collaboration, based on hierarchy of consistent **controlled** behaviors of the robot
  - residual-based collision detection (and isolation)
  - portfolio of collision reaction algorithms (using also redundancy)
  - 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
  - admittance/impedance/force/hybrid control laws, generalized at the contact level
  - some useful behaviors can be obtained also in case of limited information
  - applications are slowly coming from industrial and service stakeholders
  - many interesting research extensions ahead, some under way…

Our team at DIAG

Robotics Lab of the Sapienza University of Rome (back in 2014)

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@Stanford – Artificial Intelligence Lab - Oussama Khatib, Torsten Kröger

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- **Videos**: YouTube channel RoboticsLabSapienza. Playlist: Physical human-robot interaction