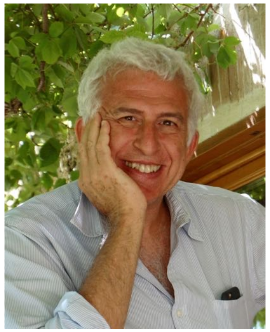
From human-robot interaction to collaborative control: A human centered perspective

Workshop @ 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems

(Organizers: Mourad Benoussaad, Arash Ajoudani, Toshiaki Tsuji, Micky Rakotondrabe)

September 27, 2021

Control of Physical Human-Robot Interaction for Safe Collaborative Tasks



Alessandro De Luca

Dipartimento di Ingegneria Informatica, Automatica e Gestionale (DIAG)

deluca@diag.uniroma1.it

SAPIENZA UNIVERSITÀ DI ROMA

IROS 2021 ONLINE

Summary

A survey of pHRI/HRC research at DIAG Sapienza in the last decade

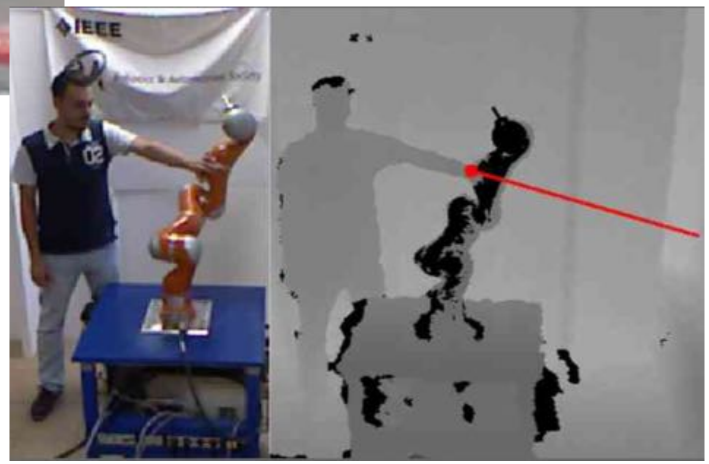
- Control architecture for physical Human-Robot Interaction/Collaboration
- Safety
  - detecting/isolating contacts and unexpected collisions in the presence of humans
  - reacting promptly in a safe mode
- Coexistence
  - human and robot actively sharing the same workspace
  - coordinated actions without contacts
- Collaboration
  - localization of physical interaction
  - estimation of exchanged forces between human and robot
  - robot control (admittance, force, impedance, hybrid motion-force, …) for collaboration
- Implementation
  - on lightweight/research robots
  - on standard industrial robots

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

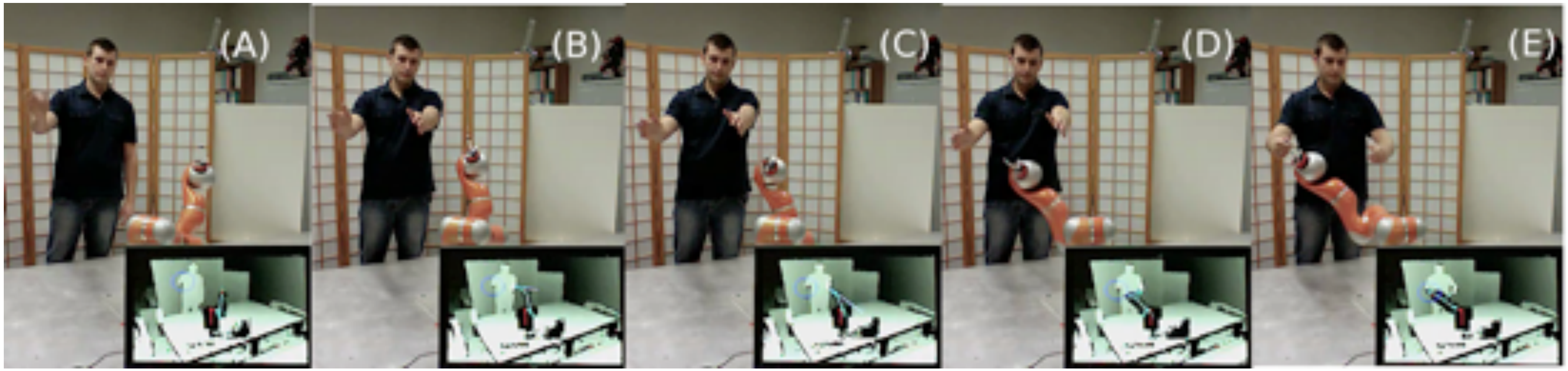
A control architecture for physical HRI

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**)

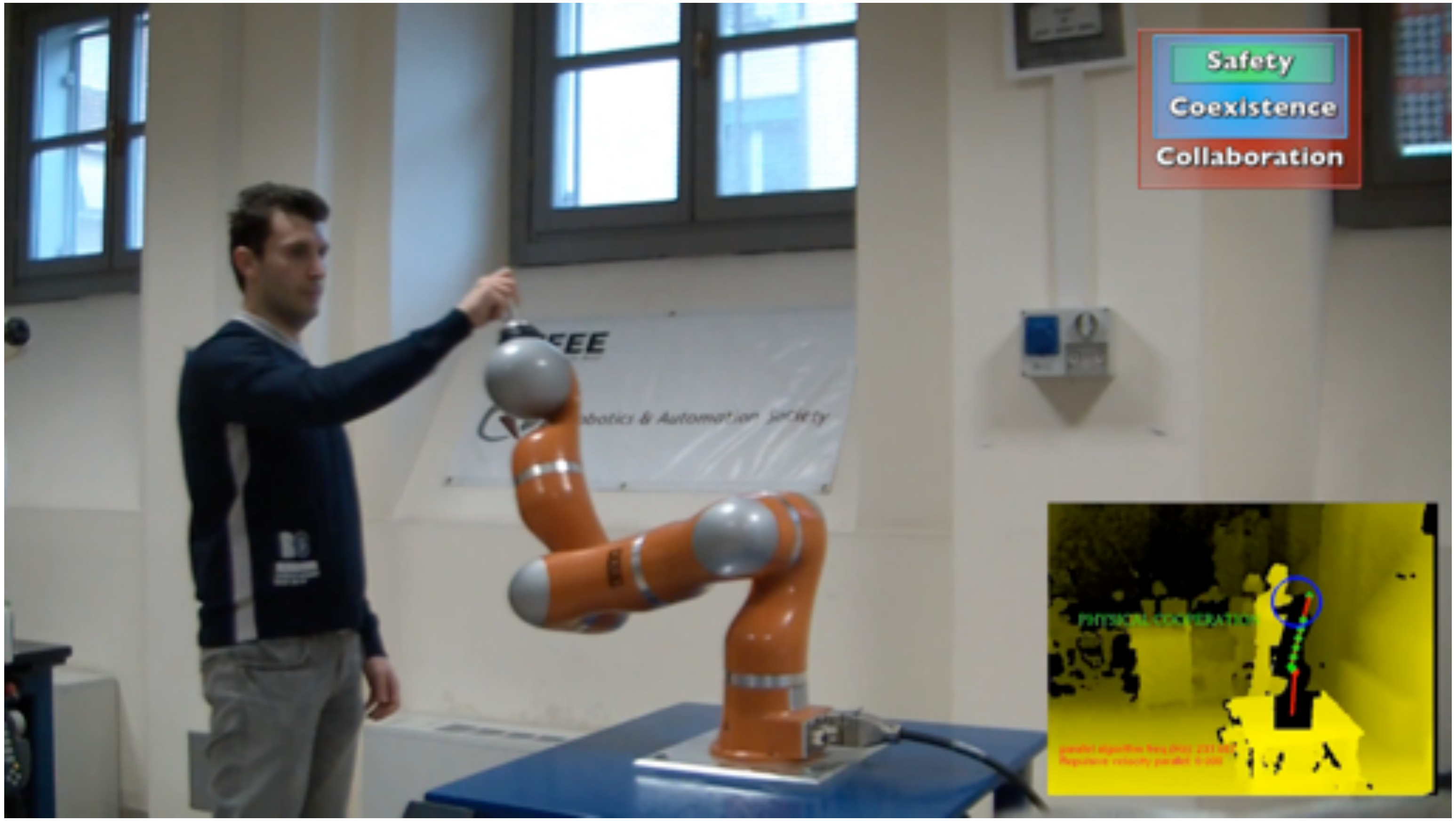
Coexistence is the robot capability of sharing the workspace with humans (**collision avoidance**)

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

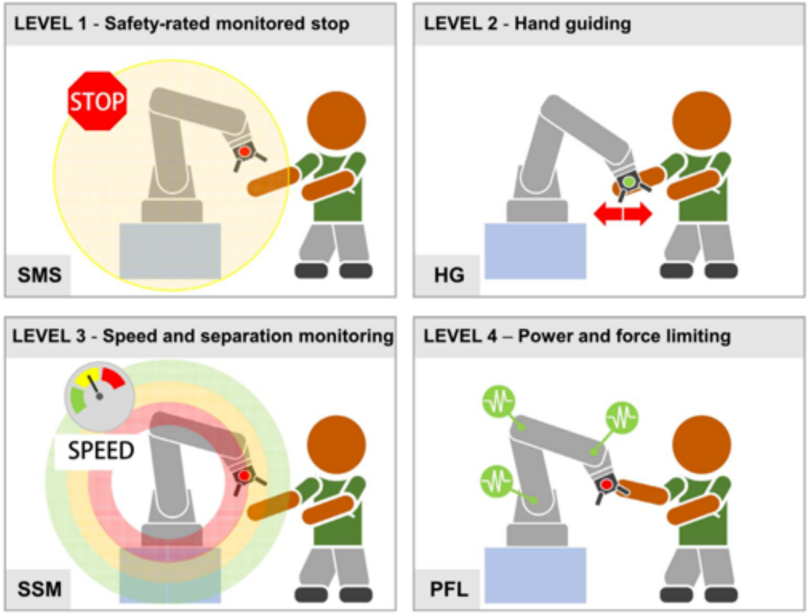


video

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

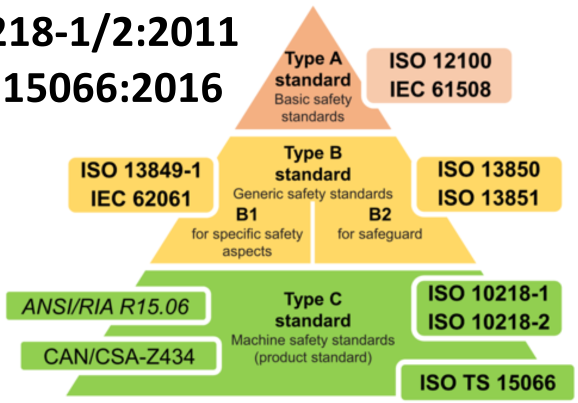
A control architecture for physical HRI

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

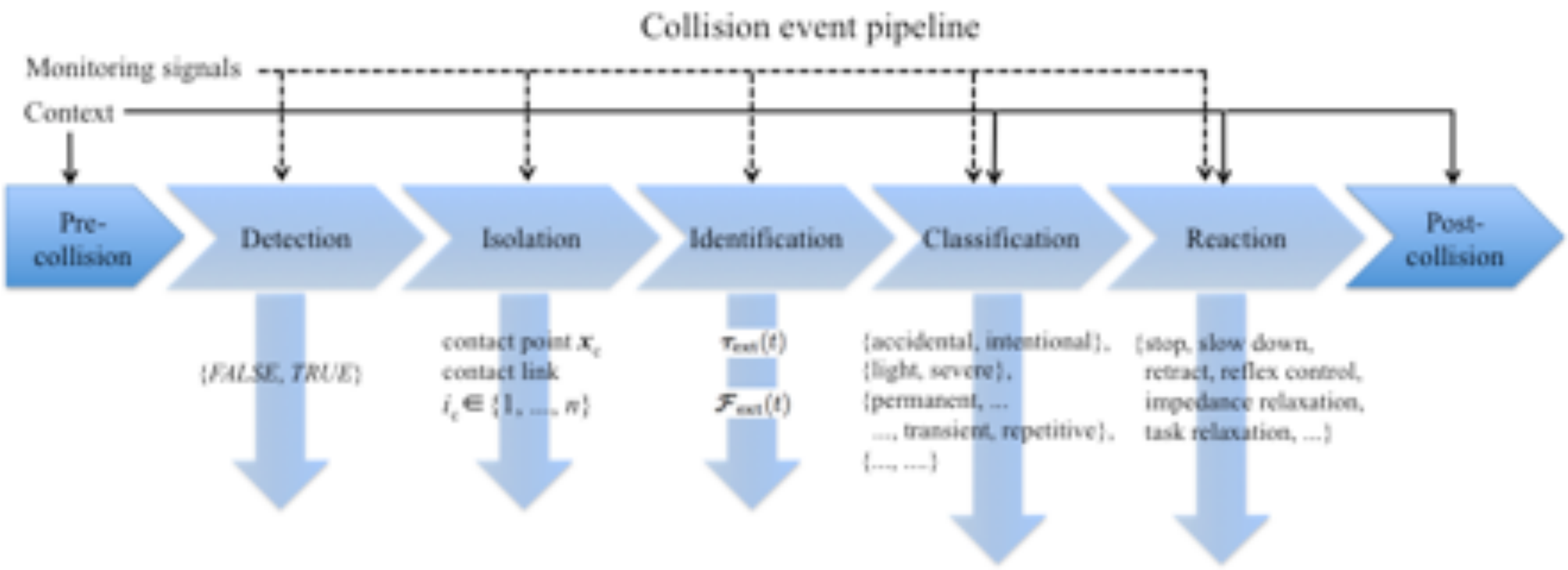
ISO 10218-1/2:2011
ISO/TS 15066:2016



- 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 2017)

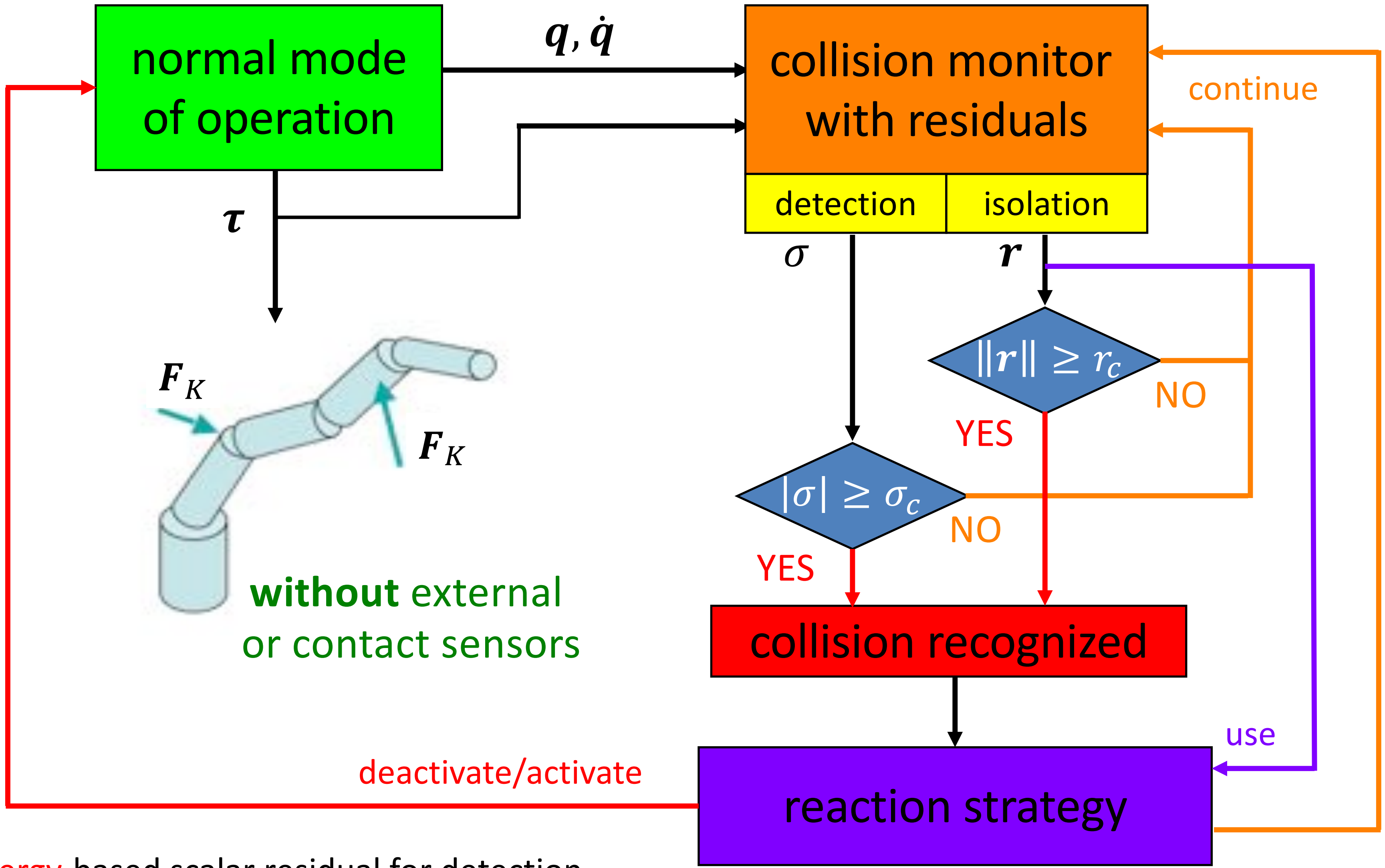


Monitoring signals can be generated from sensors or models (signal- or model-based methods)

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

Monitoring robot collisions

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

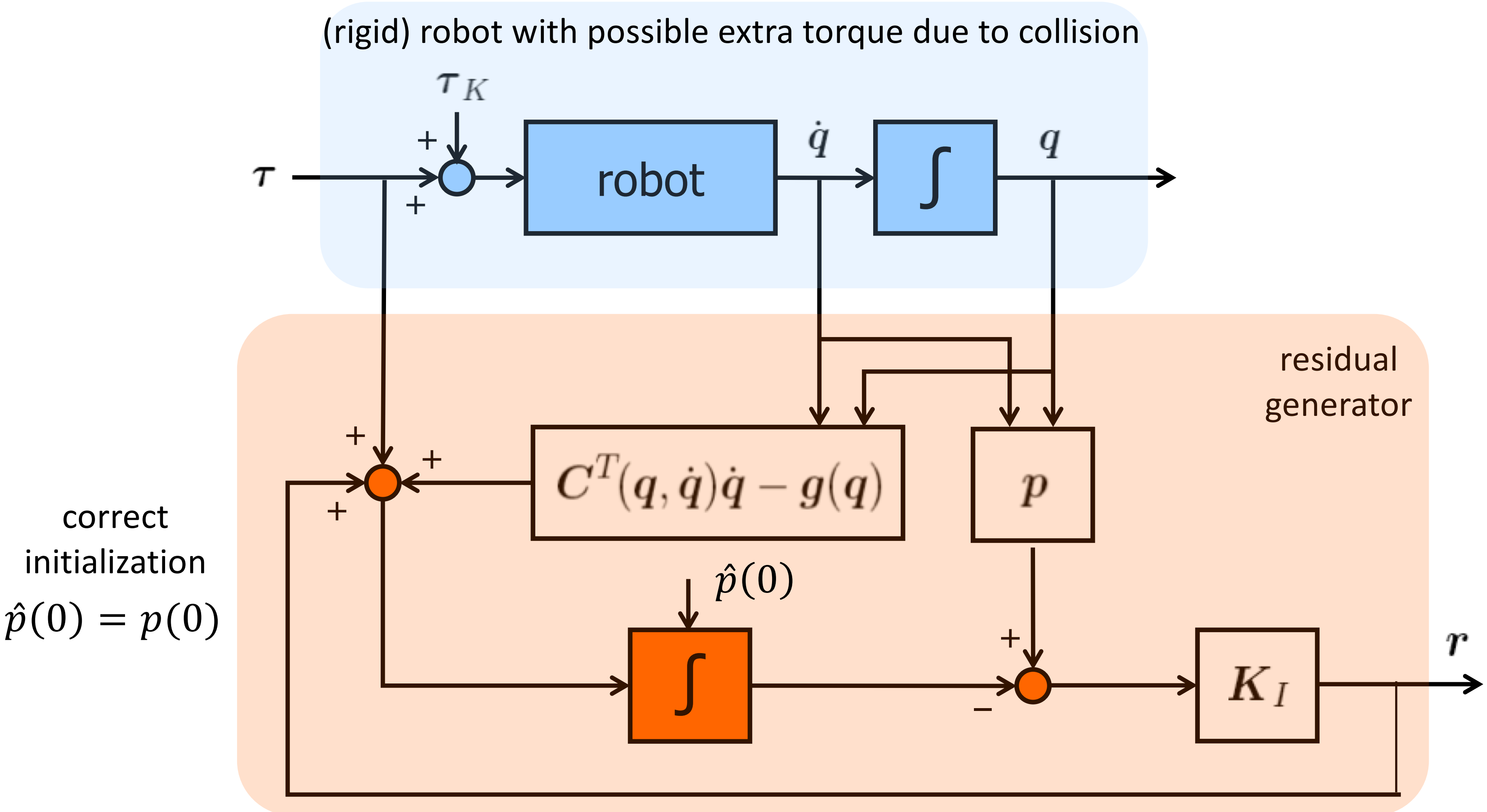


σ = energy-based scalar residual for detection

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)



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

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

3 videos

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

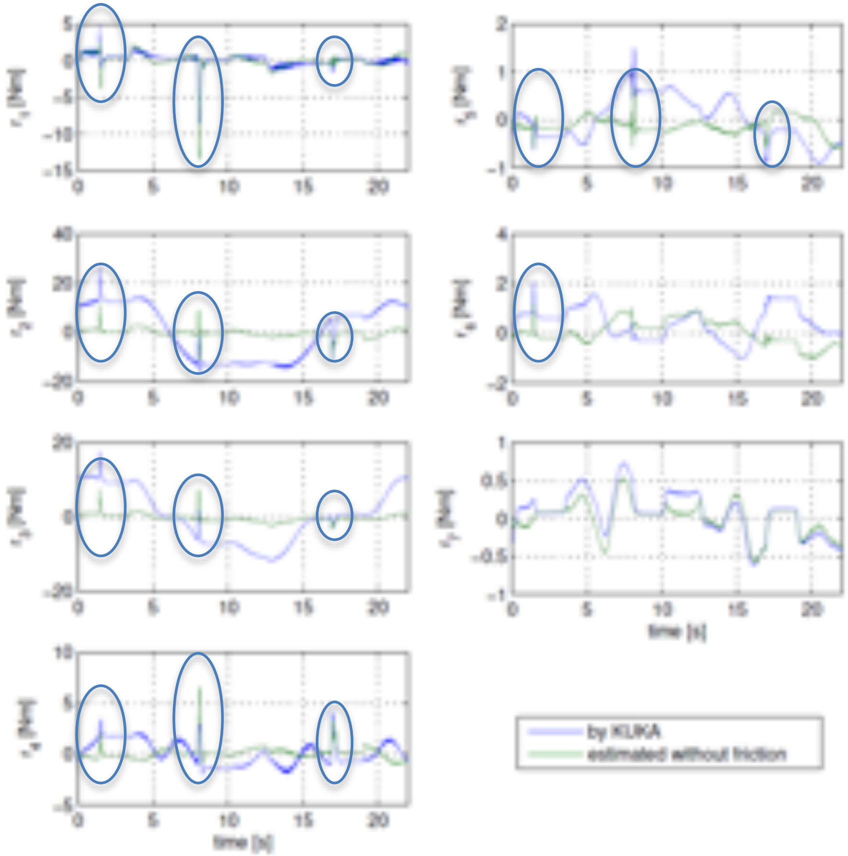
Sensitivity to payload changes/uncertainty

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

an unknown payload (of **3 kg**) is added

video

residuals with online estimated payload after 10 positioning

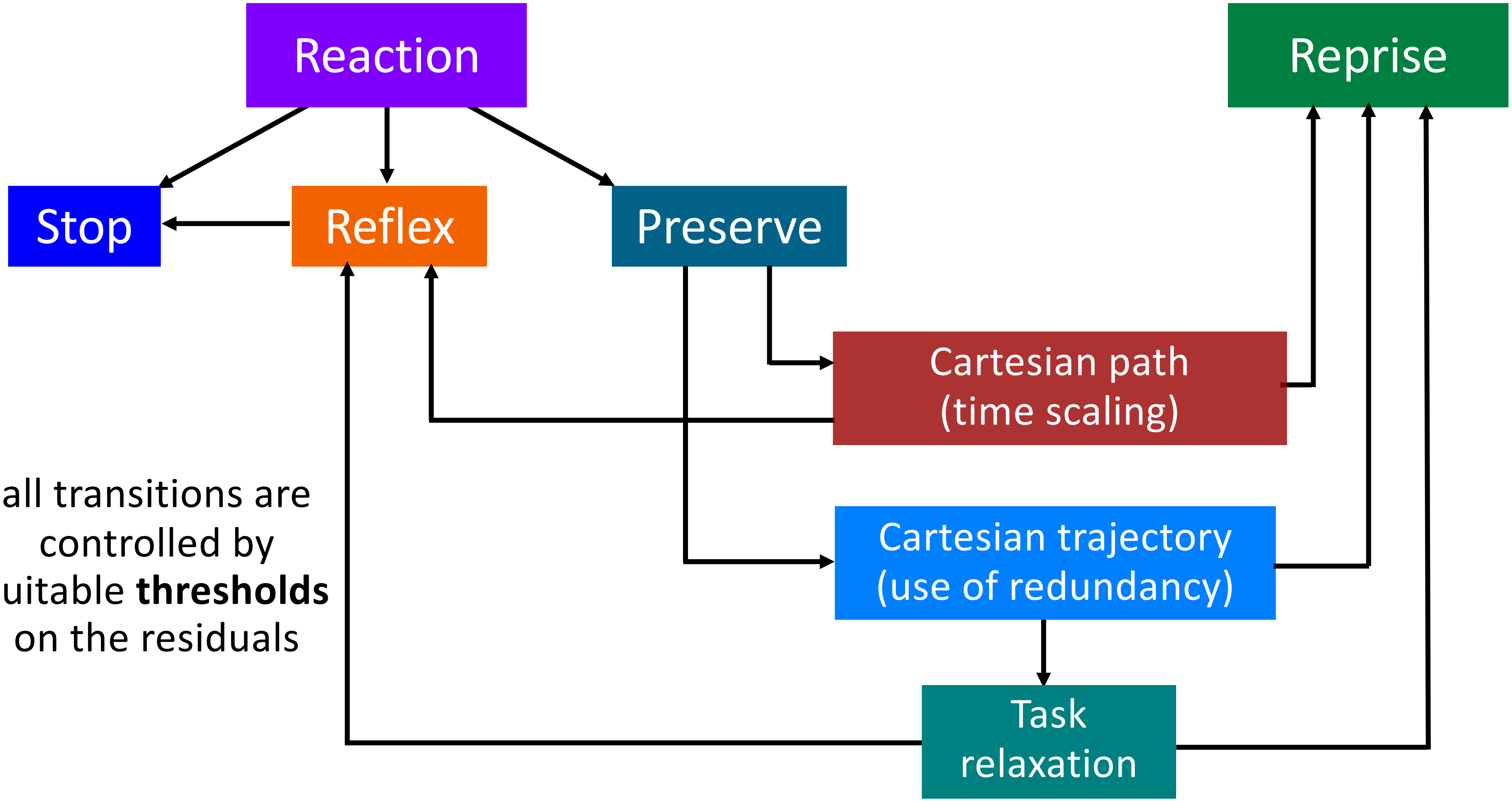


three collisions (link 6 ⇢ 5 ⇢ 5) detected & isolated by residuals when exceeding a threshold of 2 Nm

Collision reaction

Portfolio of possible robot reactions

residual amplitude ∝ severity level of collision



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

Collision reaction

Further examples (IROS 2008)

- without external sensing
- implementation using joint torque sensing (**not** strictly needed)

2 videos

- "volunteer" is Sami Haddadin (a master student at that time...)

- manipulator is position-controlled on a geometric path
- timing slows down, stops, possibly reverses

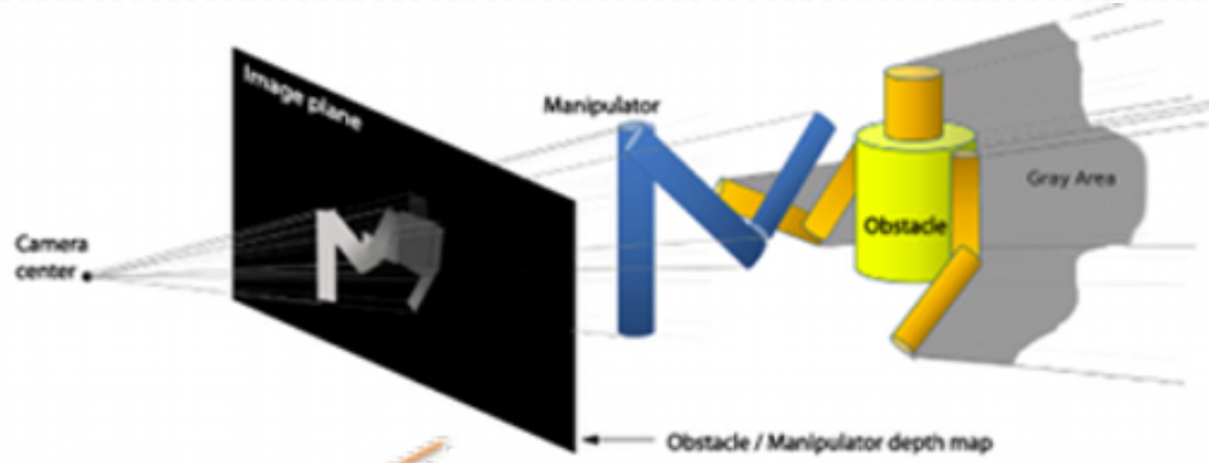
Collision avoidance working in depth space

Efficient robot-obstacle distance computations in a 2½D space (ICRA 2012)

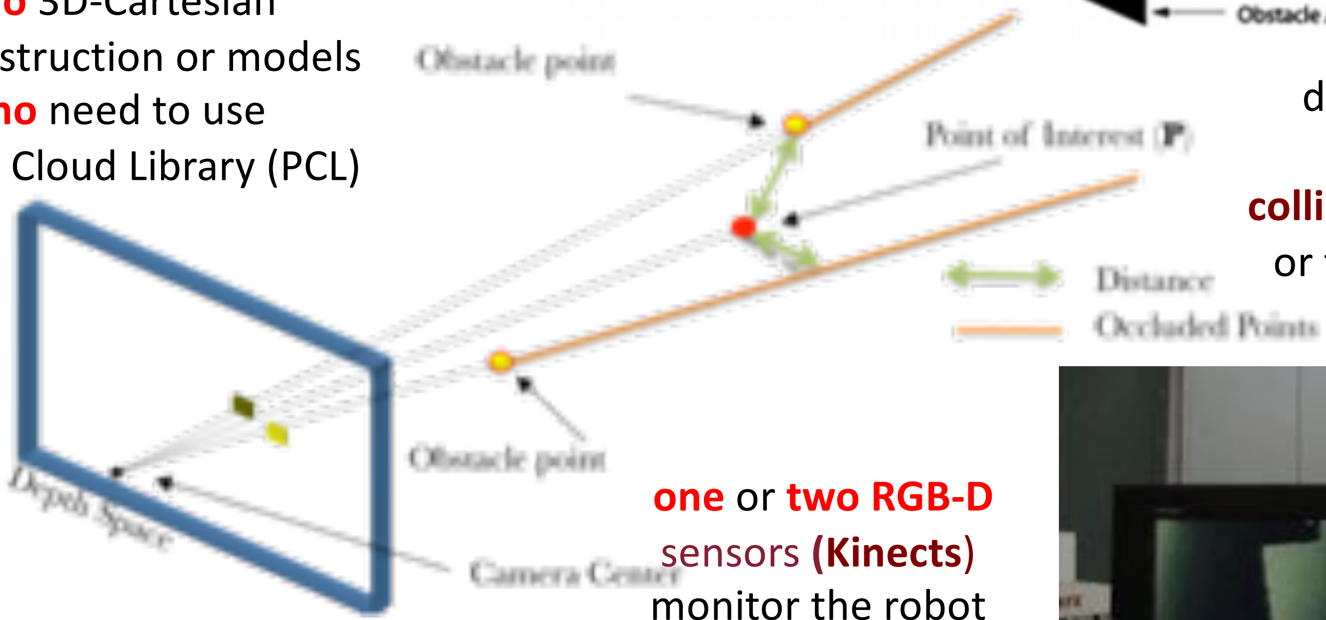
$$p_x = \frac{x_C f s_x}{z_C} + c_x$$

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

$$d_p = z_C$$



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



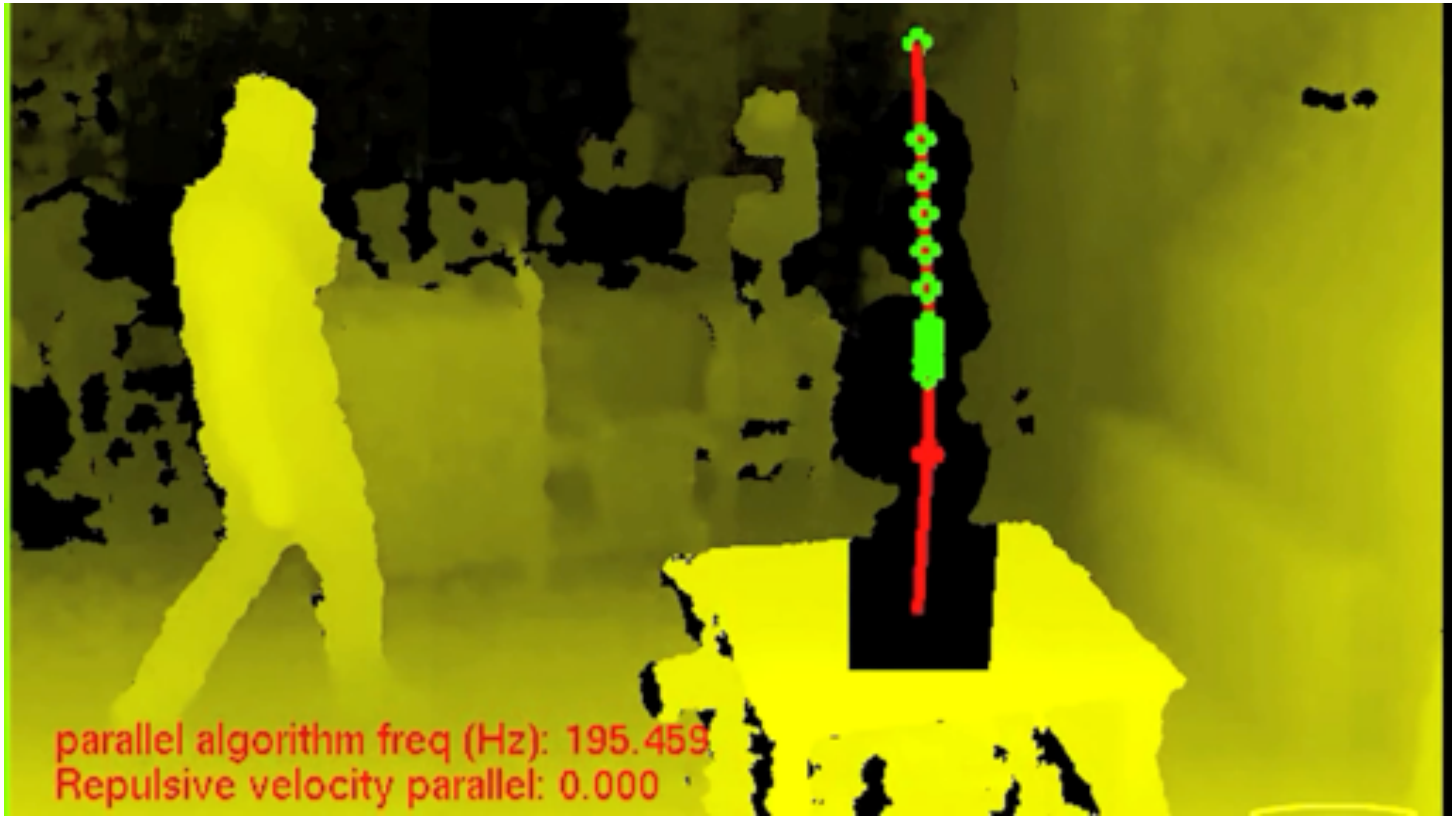
distances are used, e.g., with artificial potentials, for **collision avoidance** during motion or to **slow down/stop** the robot

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 human-robot coexistence

Excerpt from the finalist video at IROS 2013

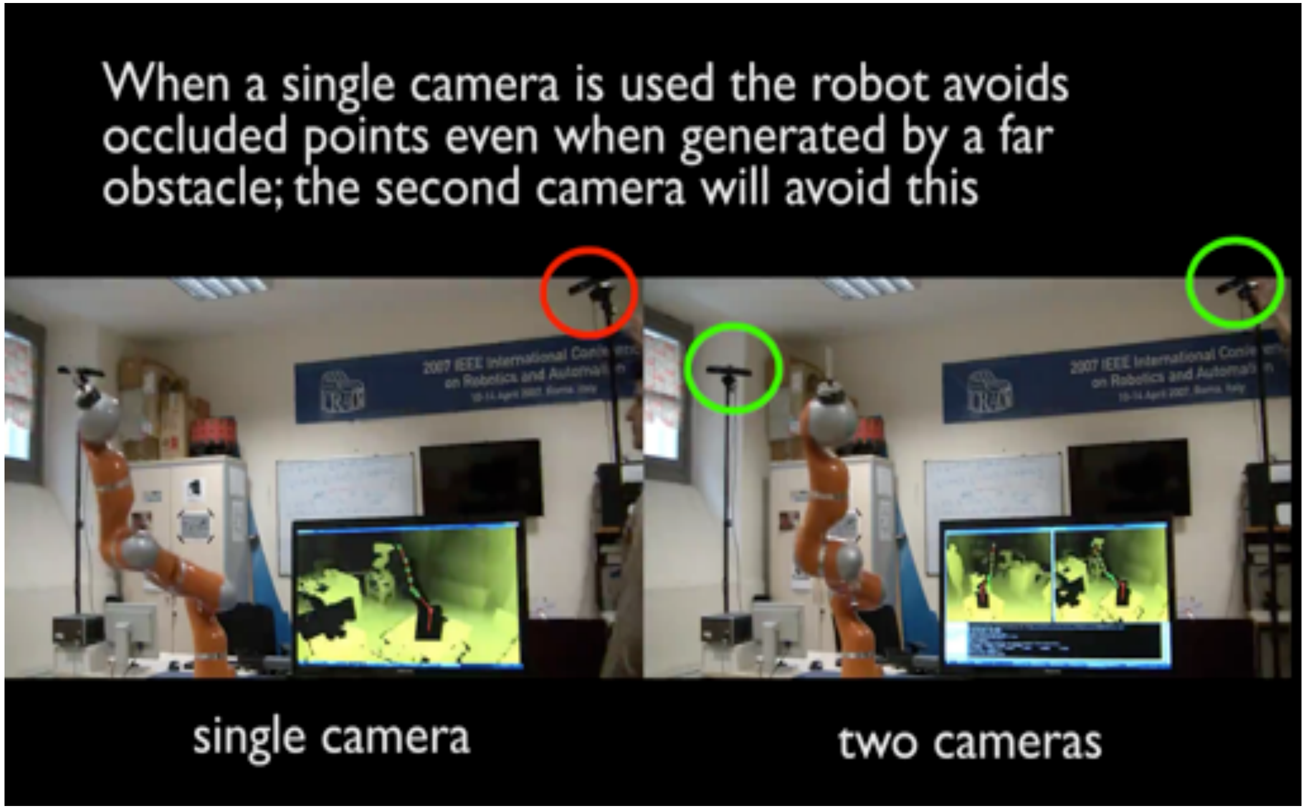


video

- **coexistence** through collision avoidance using a single Kinect
- the robot is performing a cyclic positional task in the Cartesian space

Monitoring the workspace with two Kinects

...without giving away the depth space computational approach (RA-L 2016)



video

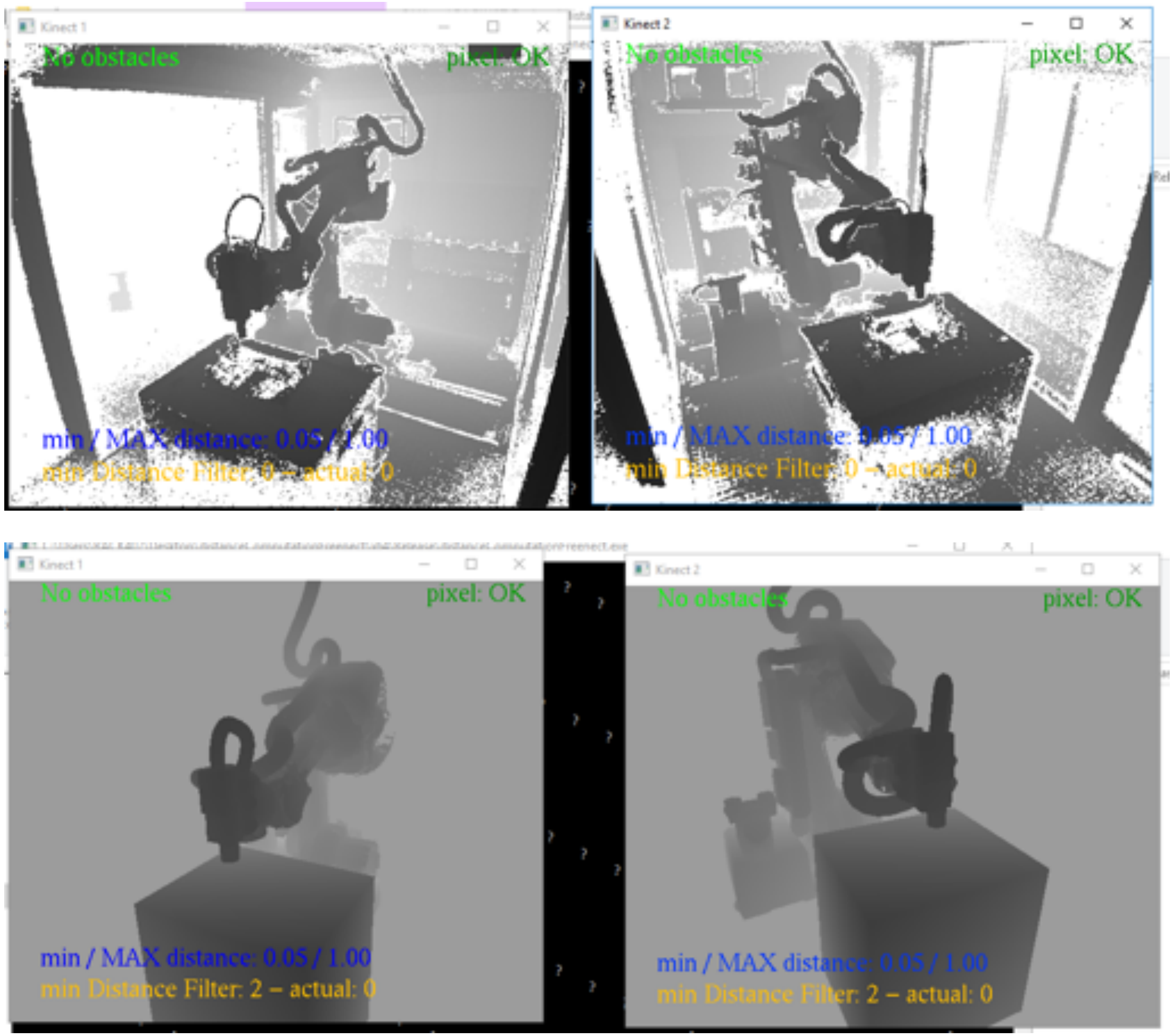
real-time efficiency
extremely fast also with 2 devices: 300 Hz rate (RGB-D camera has 30 fps, but the KUKA robot works at 0.5-1 KHz rate)

problems solved by the second camera

+ eliminates collision with false, far away "shadow" obstacles
+ reduces to a minimum gray areas, thus detects what is "behind" the robot
+ calibration is done off-line

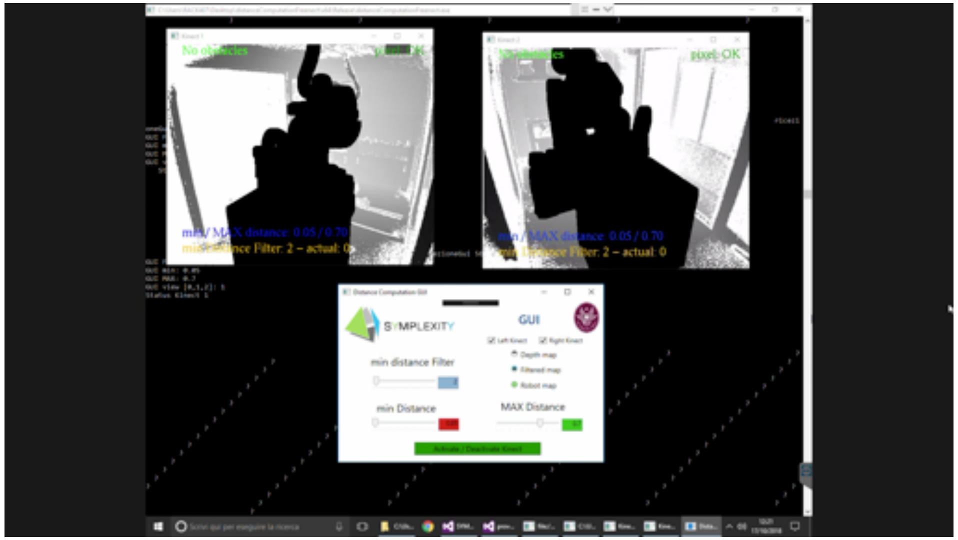
CAD model of the robot and equipments/tools/cables

Filtering out the right parts from the depth images



Safe coexistence in an industrial robotic cell

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



2 videos

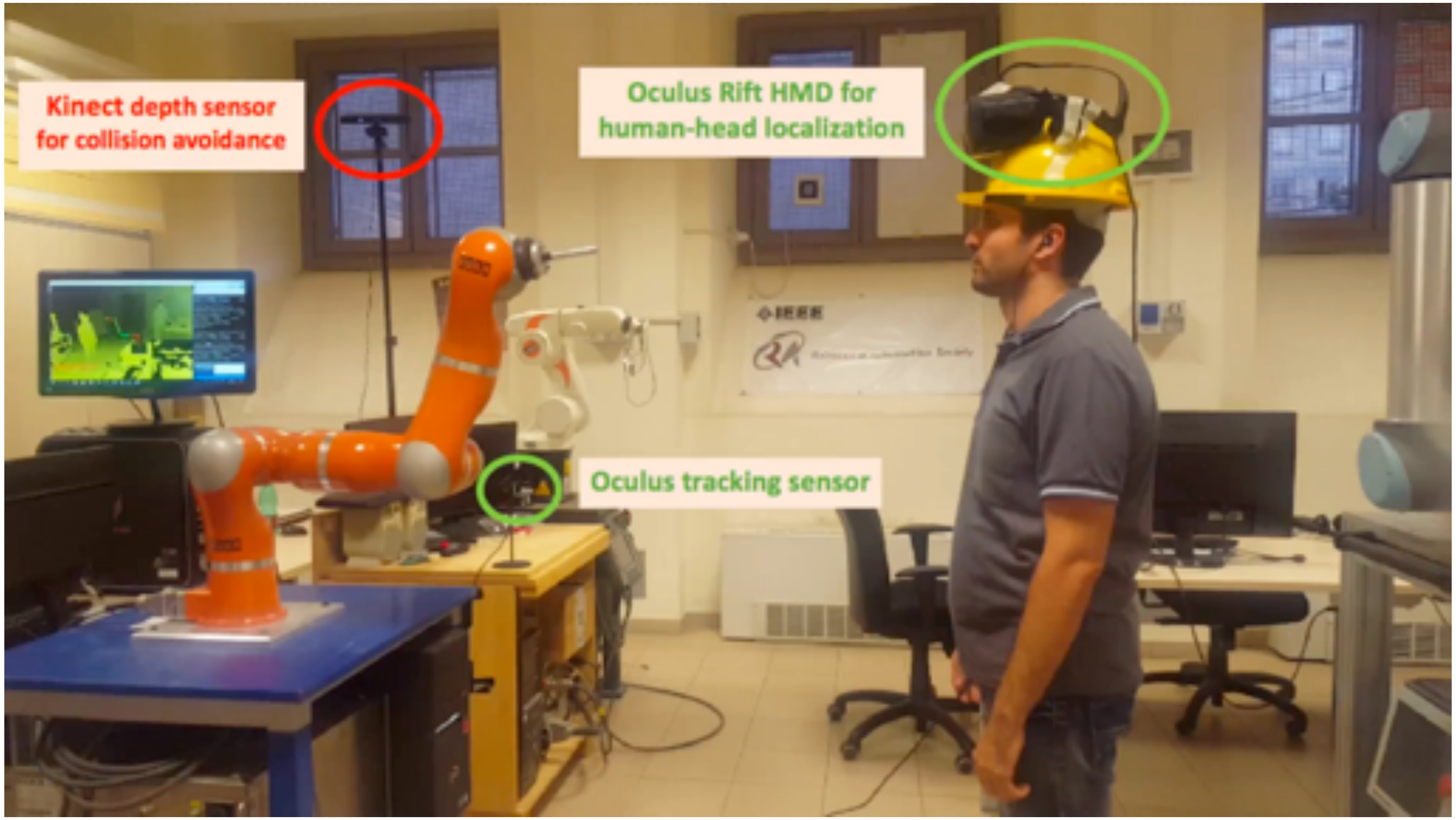
depth images and GUI

- the robot is moving at max 100 mm/s
- no safety zones were defined in the ABB SafeMove software
- a risk analysis & a mitigation plan on the Kinect 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

Coexistence with visual coordination

Robot motion coordinated with the human, avoiding proximity (IROS 2017, RCIM 2021)



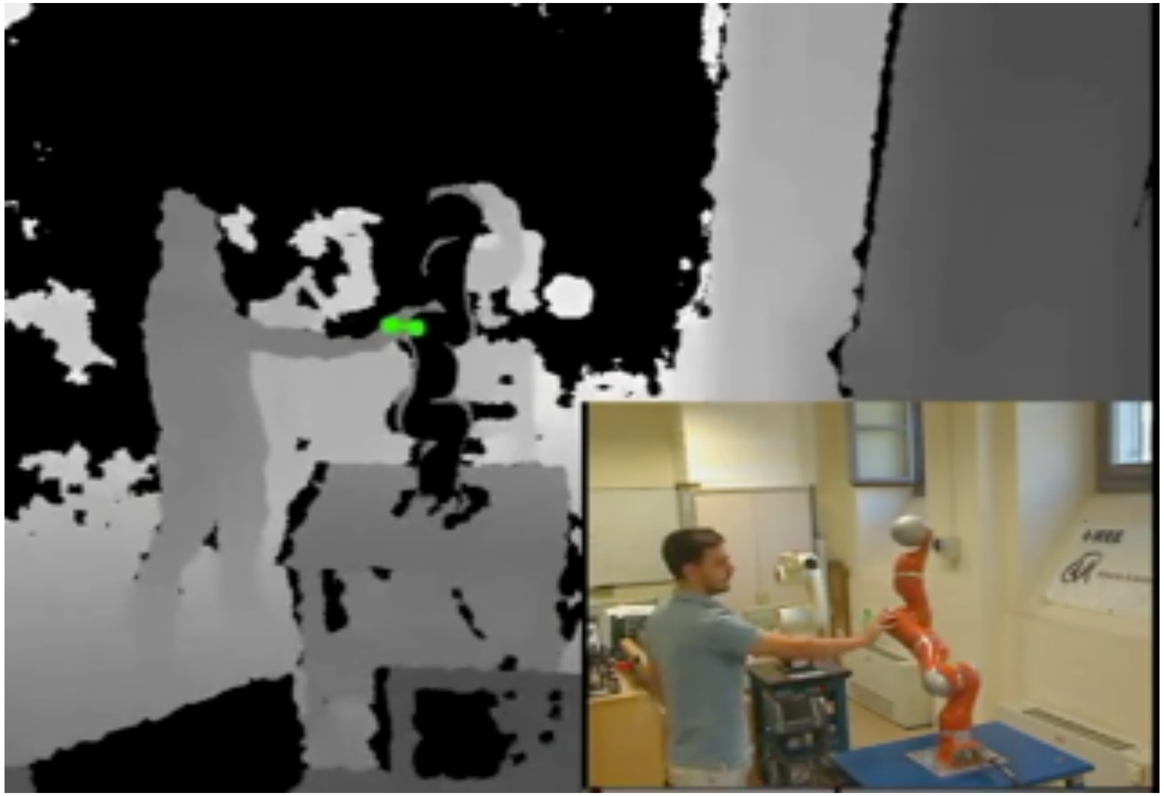
video

- the robot tracks remotely & points to the head of the human (wearing Oculus Rift)
- it reacts so as to keep a safe distance to human and environment obstacles

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

- **parallel** GPU computation on **CUDA framework**: distances between all robot points in virtual depth image and all obstacle points in filtered depth image (IROS 2017)

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
  - 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 **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

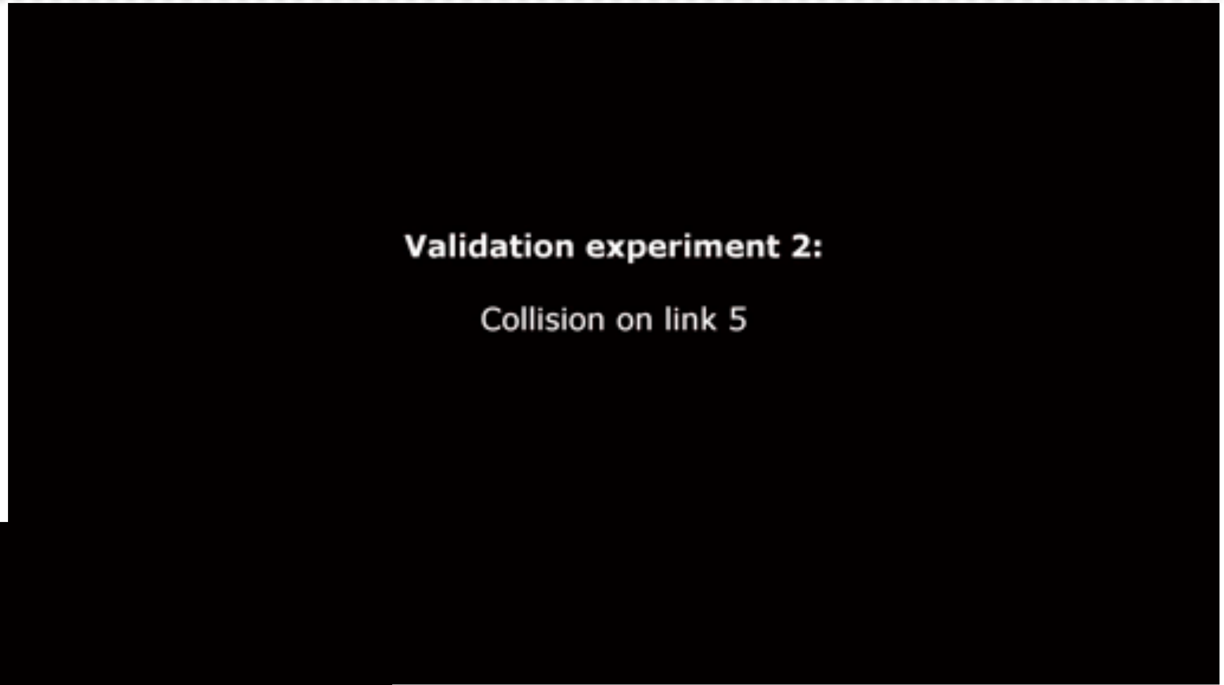
Used within an admittance control scheme (IROS 2014)

video

Additional 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)

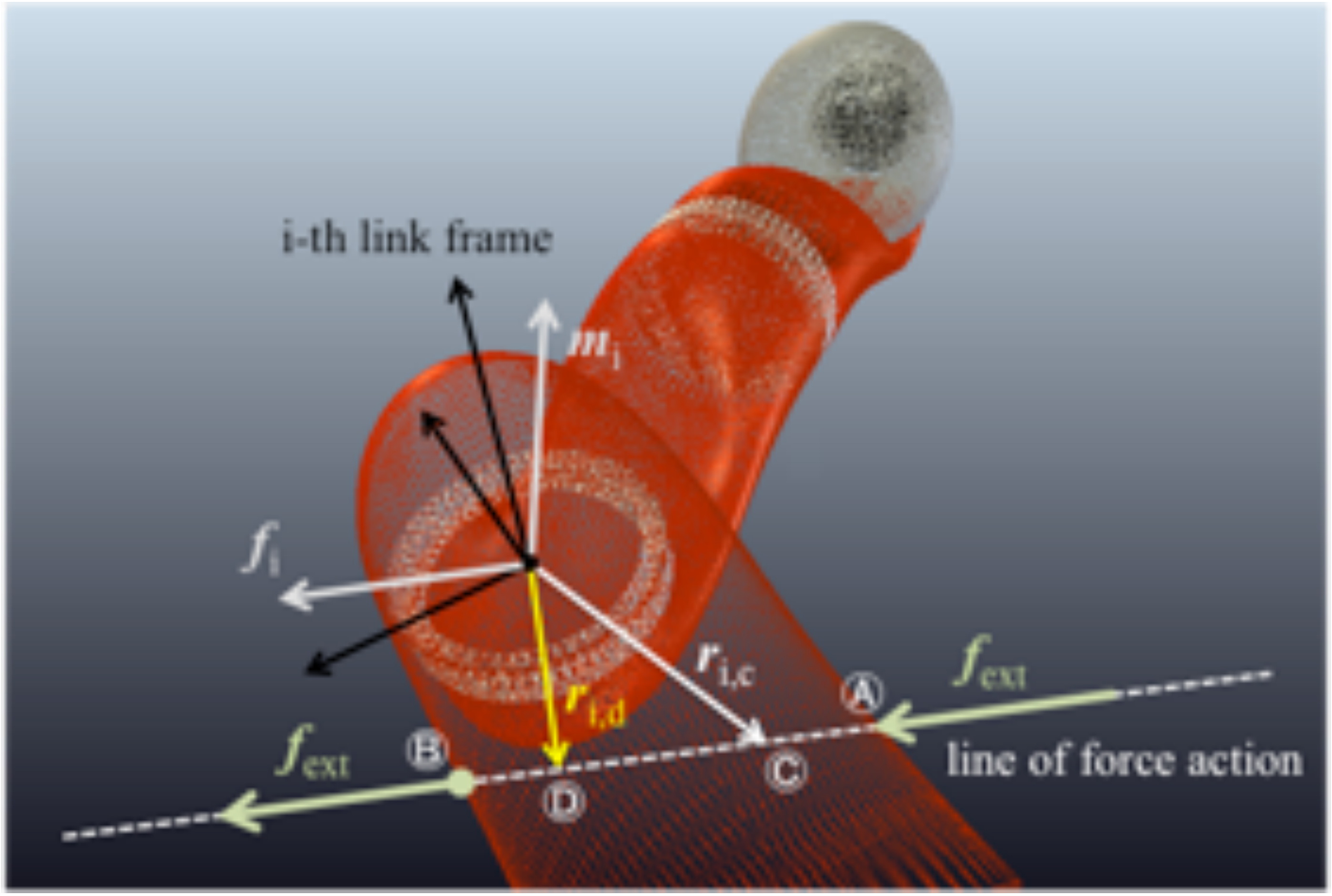


2 videos

Estimation of the contact force

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

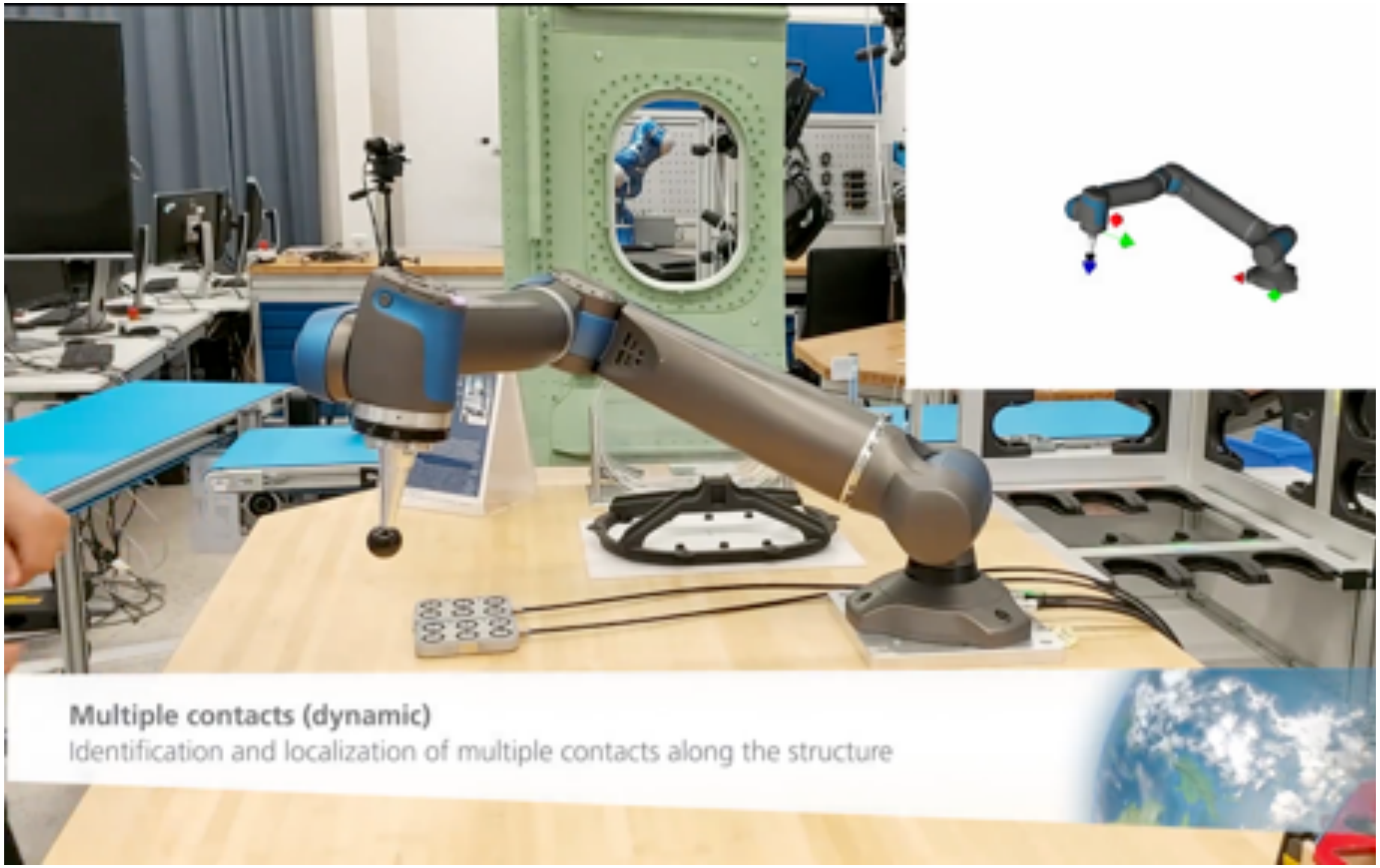
- if contact is sufficiently "down" the kinematic chain (≥ 6 residuals are available), the estimation of pure contact forces does not need any external information ...



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 the redundant sensing system
- handles multiple contacts, singularities, and external force/torque estimation



video

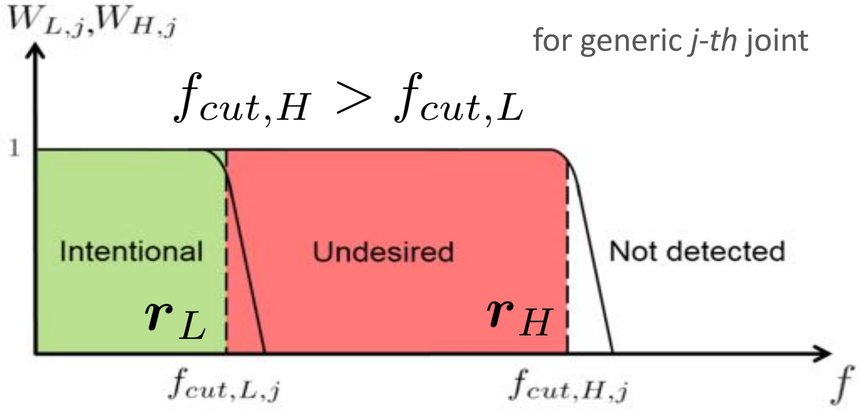
Collision or collaboration?

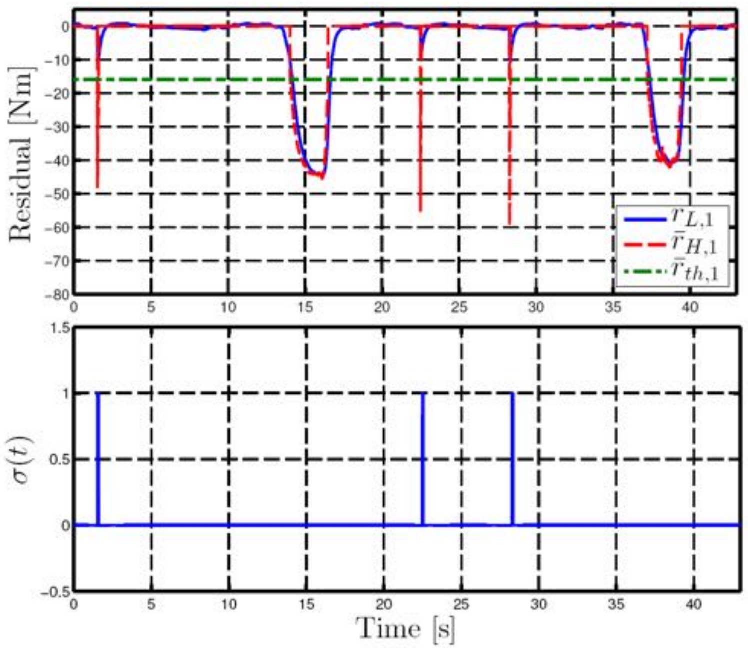
Distinguishing hard/accidental collisions and soft/intentional contacts

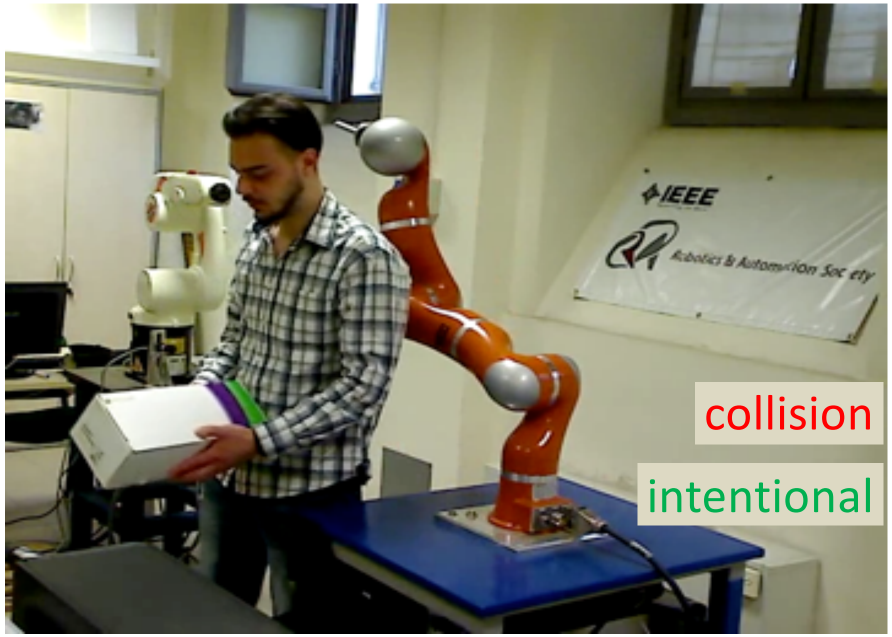
- using suitable low and high bandwidths for the residuals (first-order stable filters)

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

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







video

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

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

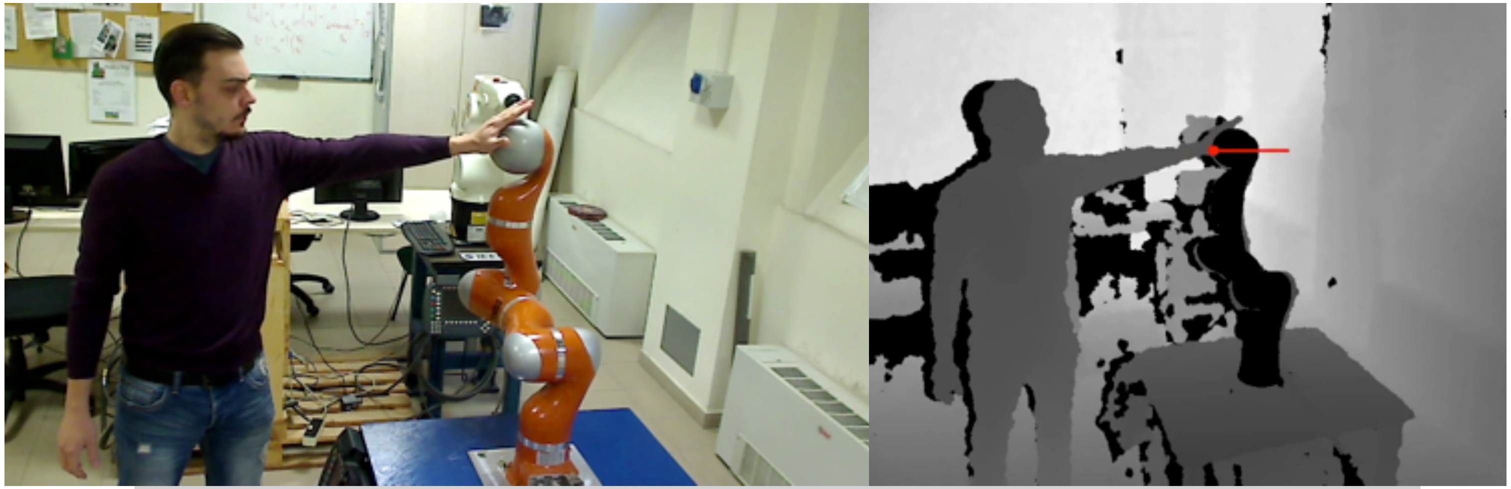
$$\boldsymbol{F}_a = \widehat{\boldsymbol{F}}_c + \boldsymbol{K}_p(\boldsymbol{p}_d - \boldsymbol{p}_c), \qquad \boldsymbol{K}_p = k_p \boldsymbol{I} > 0$$

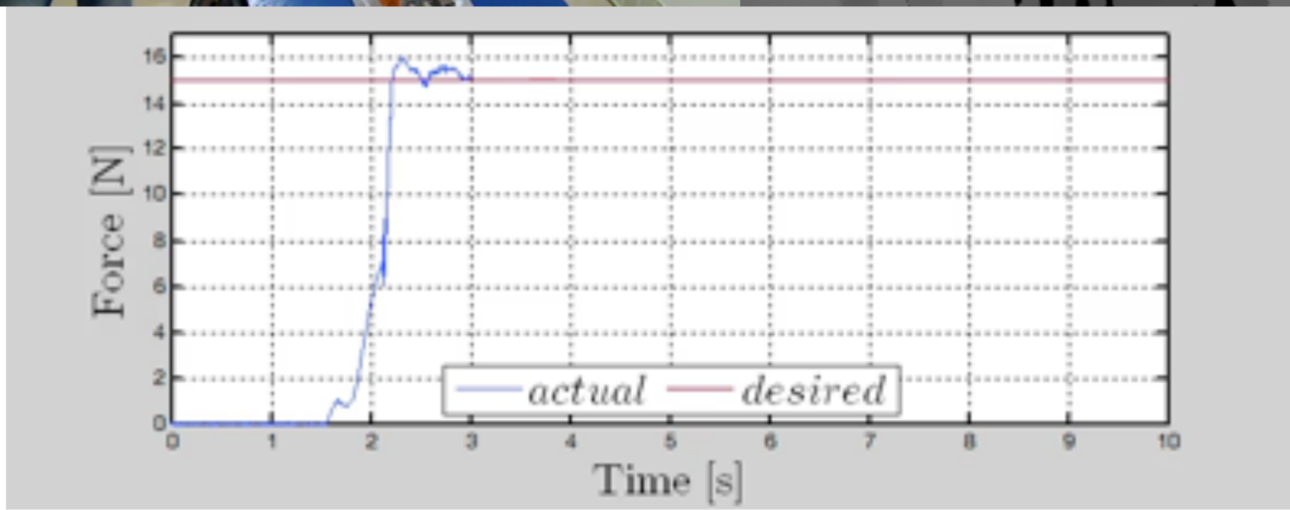
↖ initial contact point position when interaction begins

Contact force regulation with virtual force sensing

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

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





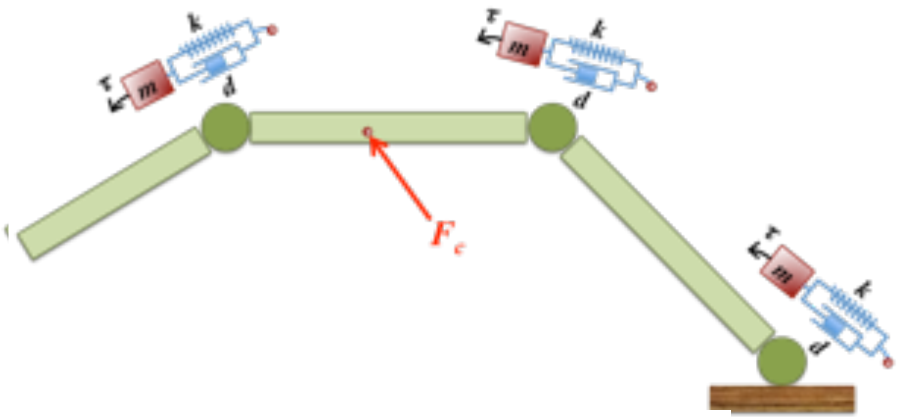
video

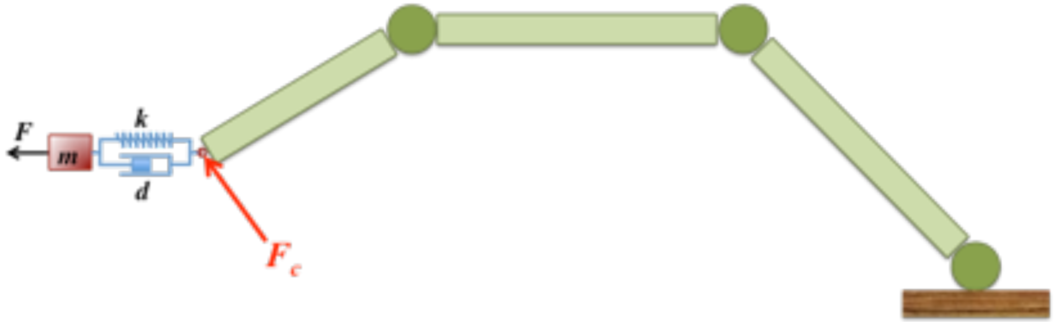
see **ICRA 2015 trailer** (at 3’26’’): https://youtu.be/glNHq7MpCG8 (Italian); https://youtu.be/OM_1F33fcWk (English)

Impedance-based control of interaction

Reaction to contact forces by generalized impedance —at different levels

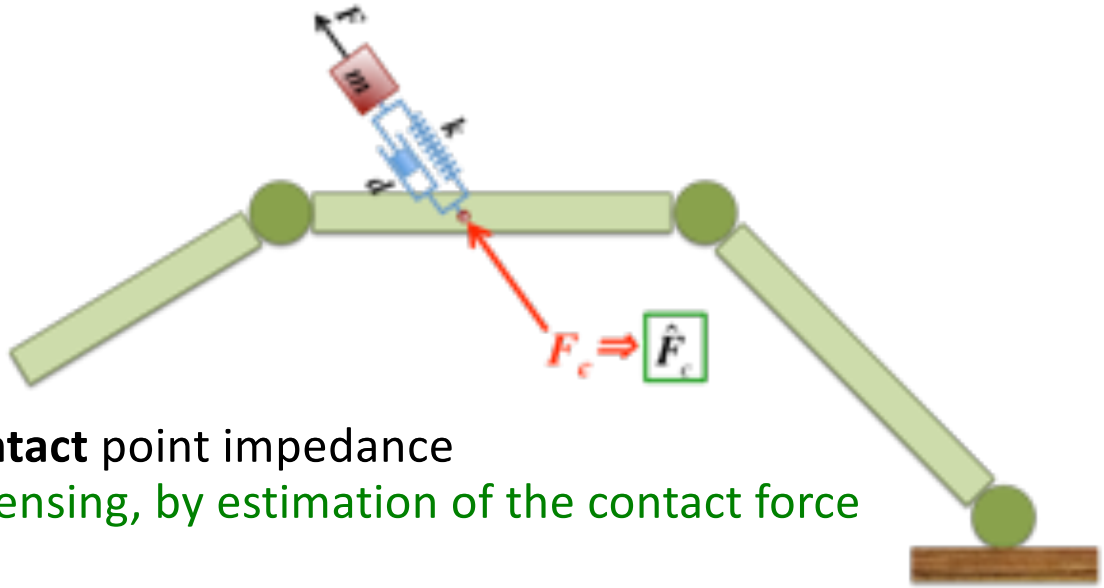
consider a fully rigid robot





Joint impedance
needs joint torque sensors

Cartesian impedance
needs F/T sensor



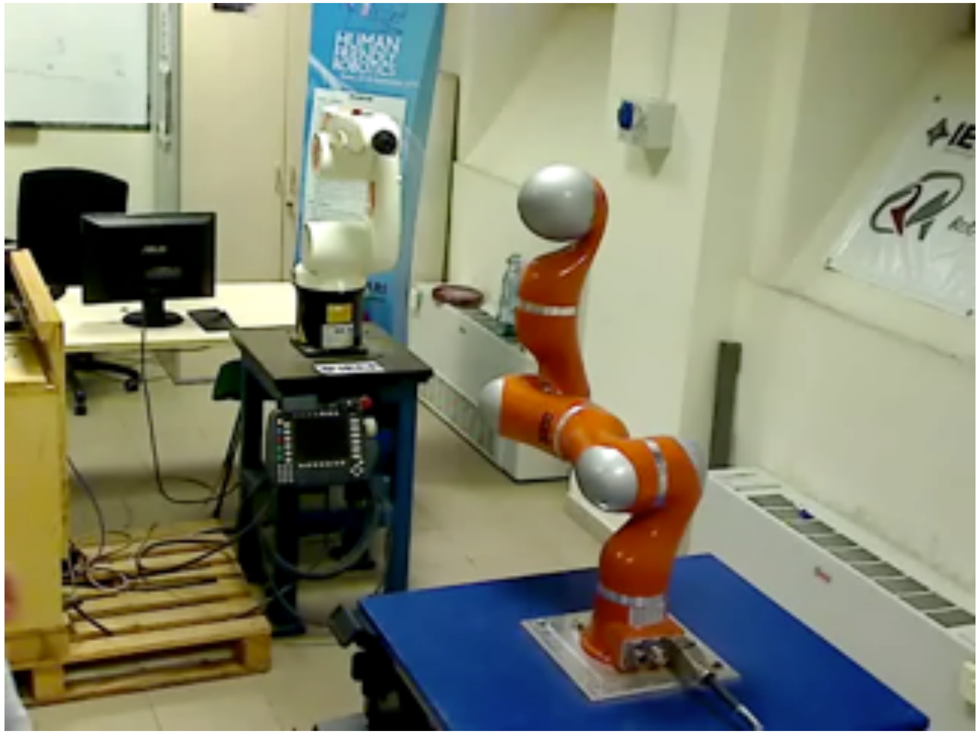
Contact point impedance
without force/torque sensing, by estimation of the contact force

Control of generalized impedance

HR collaboration at the contact level (ICRA 2015)

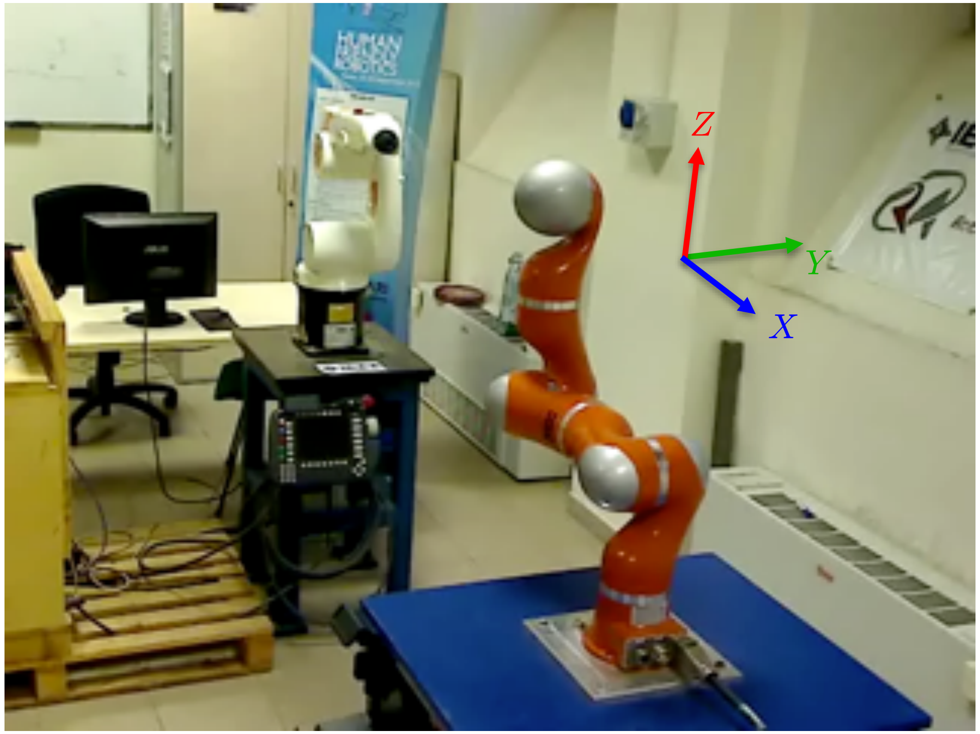
natural (unchanged) robot inertia at the contact

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



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

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



2 videos

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])

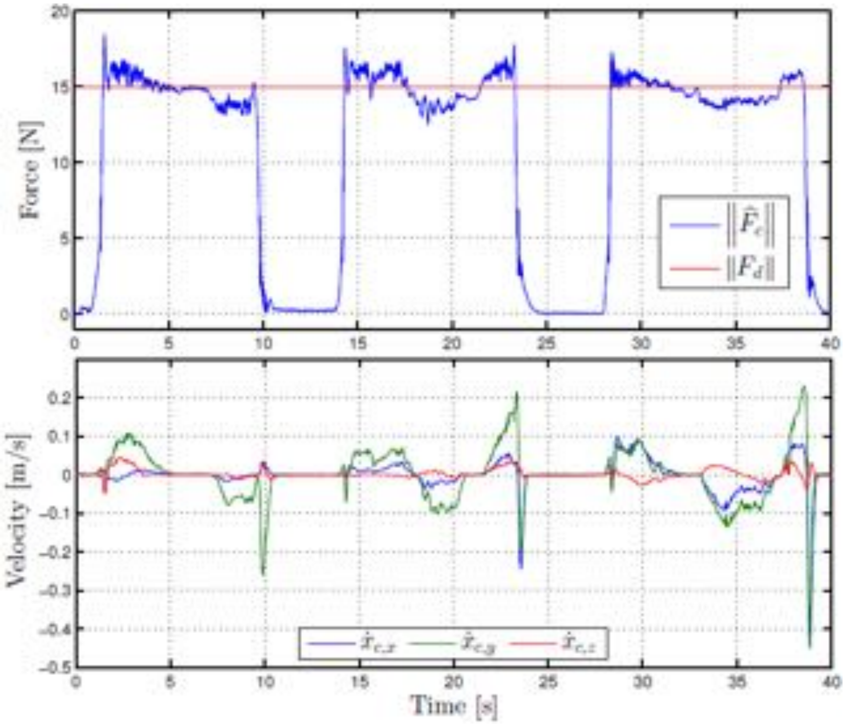
Control of generalized contact force

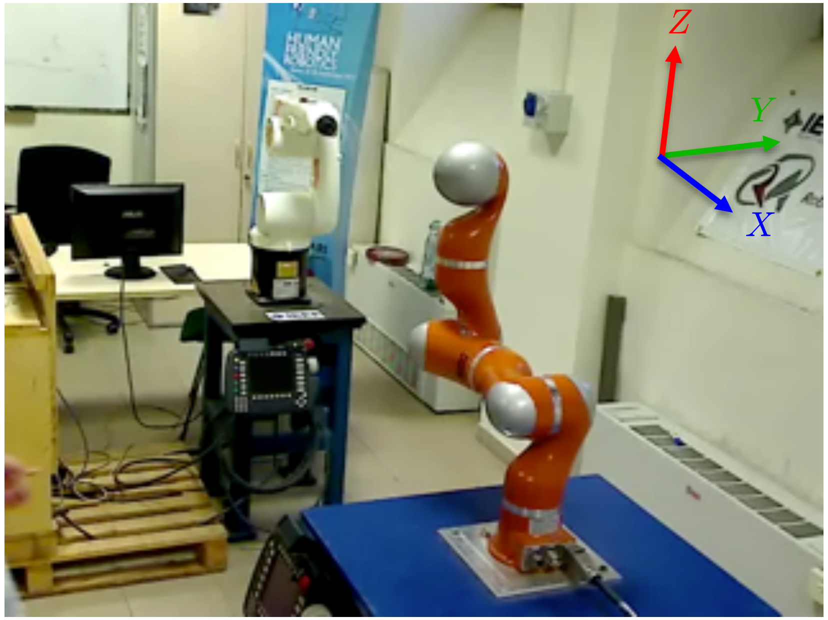
Task-compatible force control scheme (ICRA 2015)

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

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

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





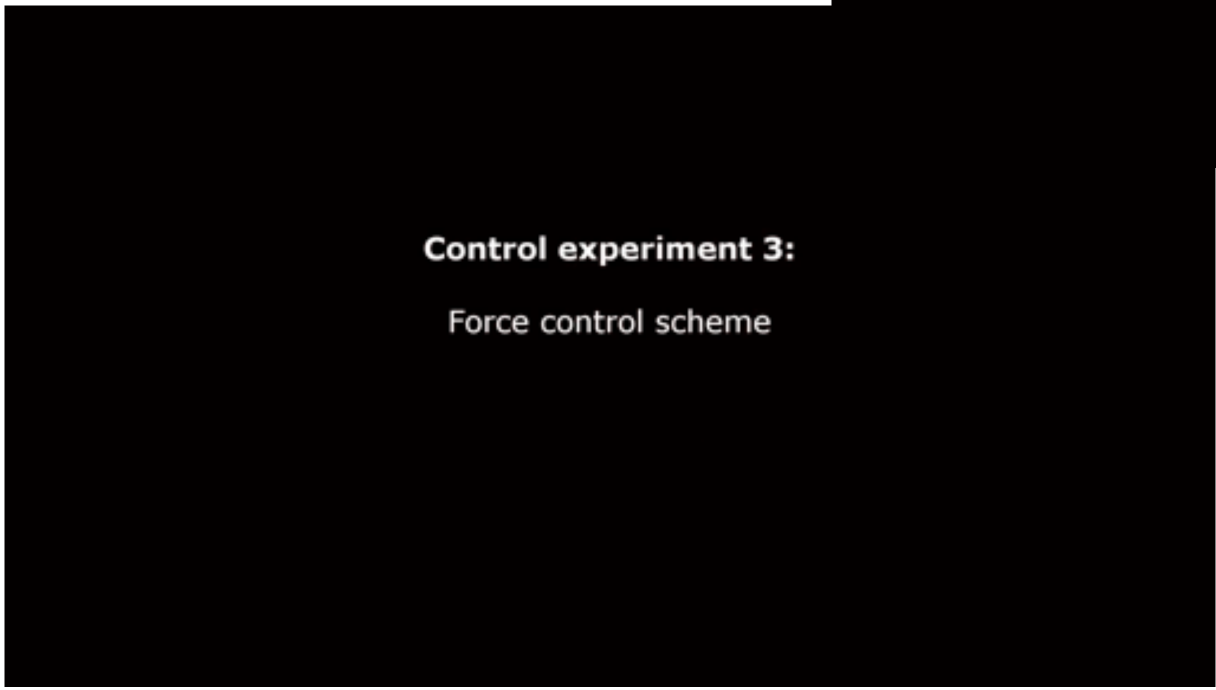
video

task-compatible control of contact force

Validation with an extra F/T sensor

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

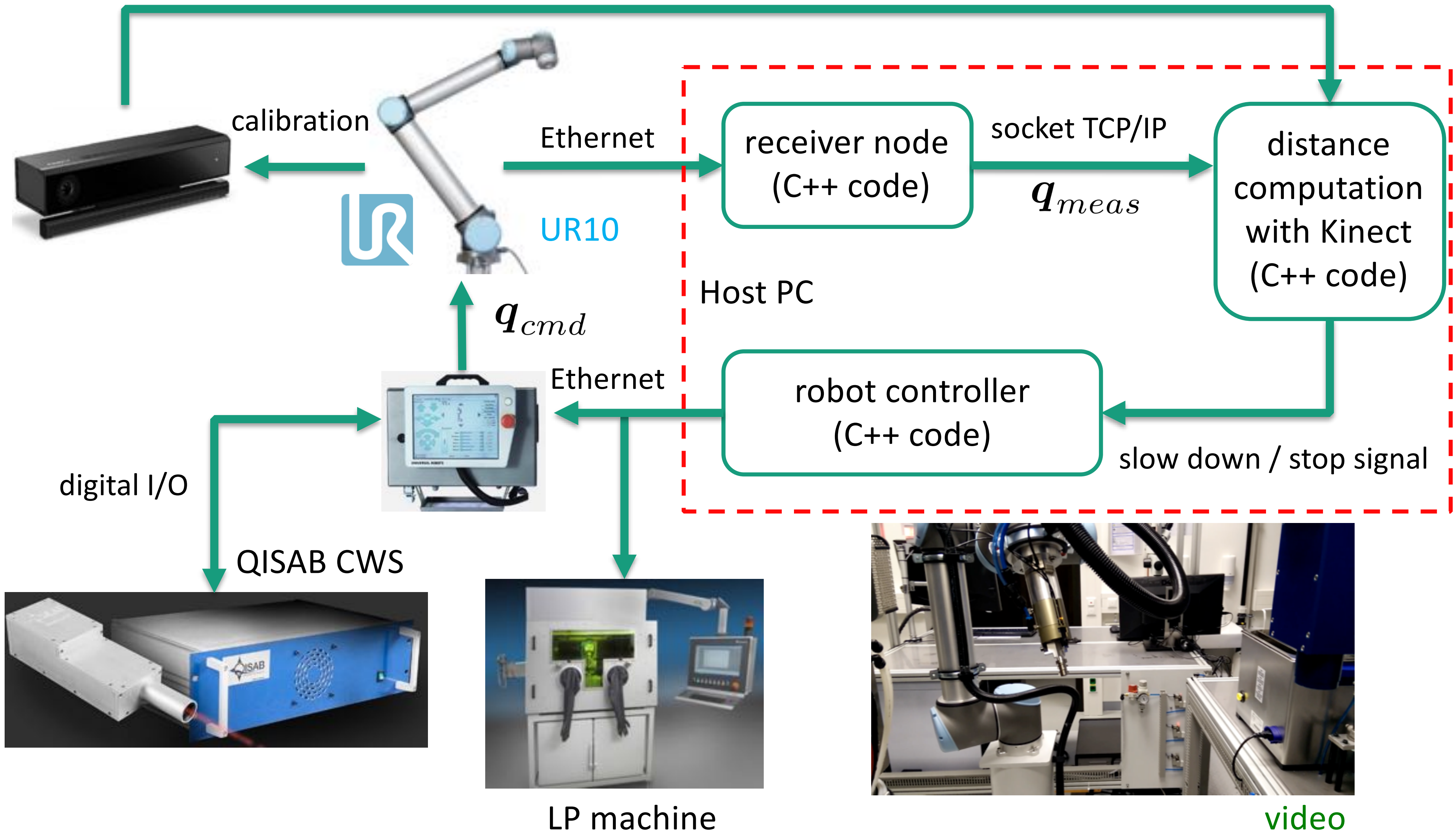
- desired contact force along the estimated contact direction regulated at 15 N
- … and trajectory control with constant speed along a circle in the orthogonal plane



2 videos

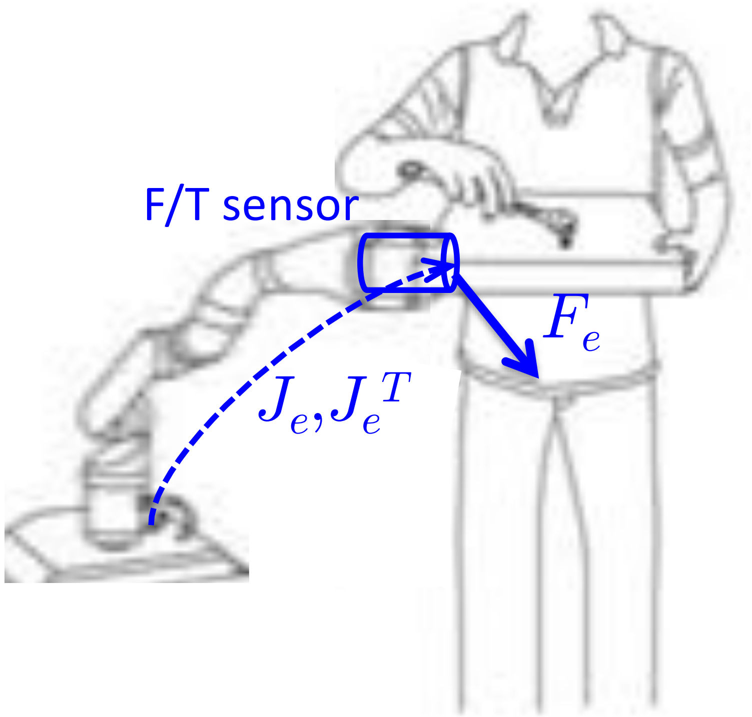
Scenario for HRC in manual polishing

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



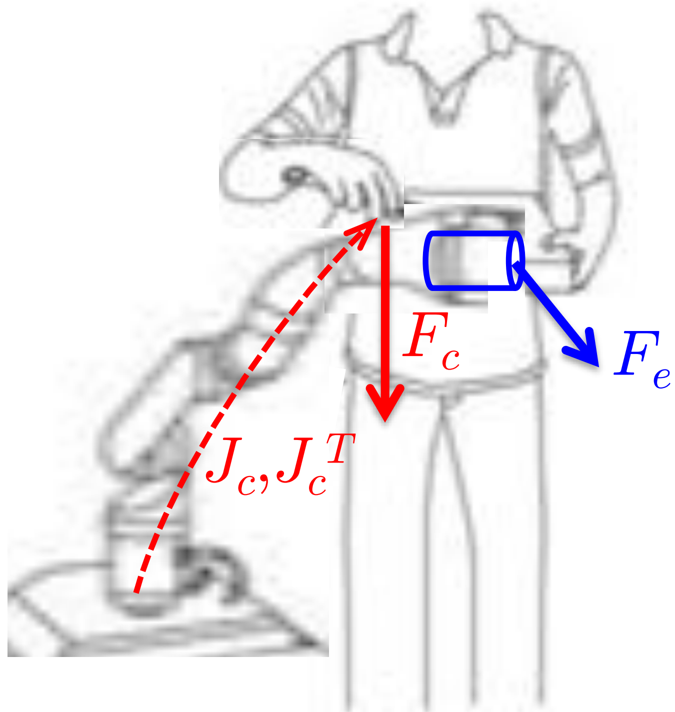
Scenario for HRC in manual polishing

Distinguishing different contact forces (with F/T sensor)



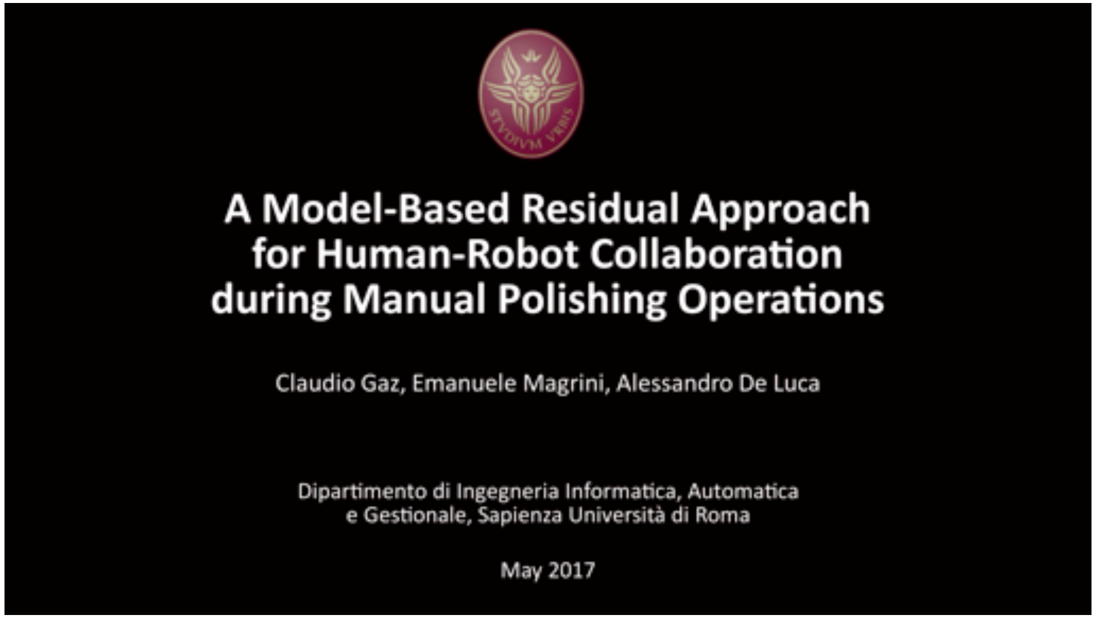
Force/Torque (F/T) sensor at wrist
- manual polishing force is **measured**
- end-effector Jacobian is **known**

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

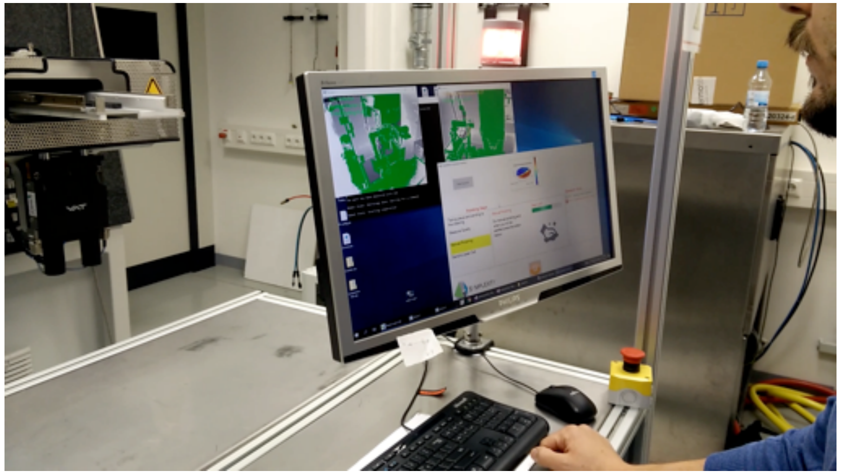
Experimental results (Mechatronics 2018)



no F/T sensor, switching to FreeDrive mode

with F/T sensor, using our residual method

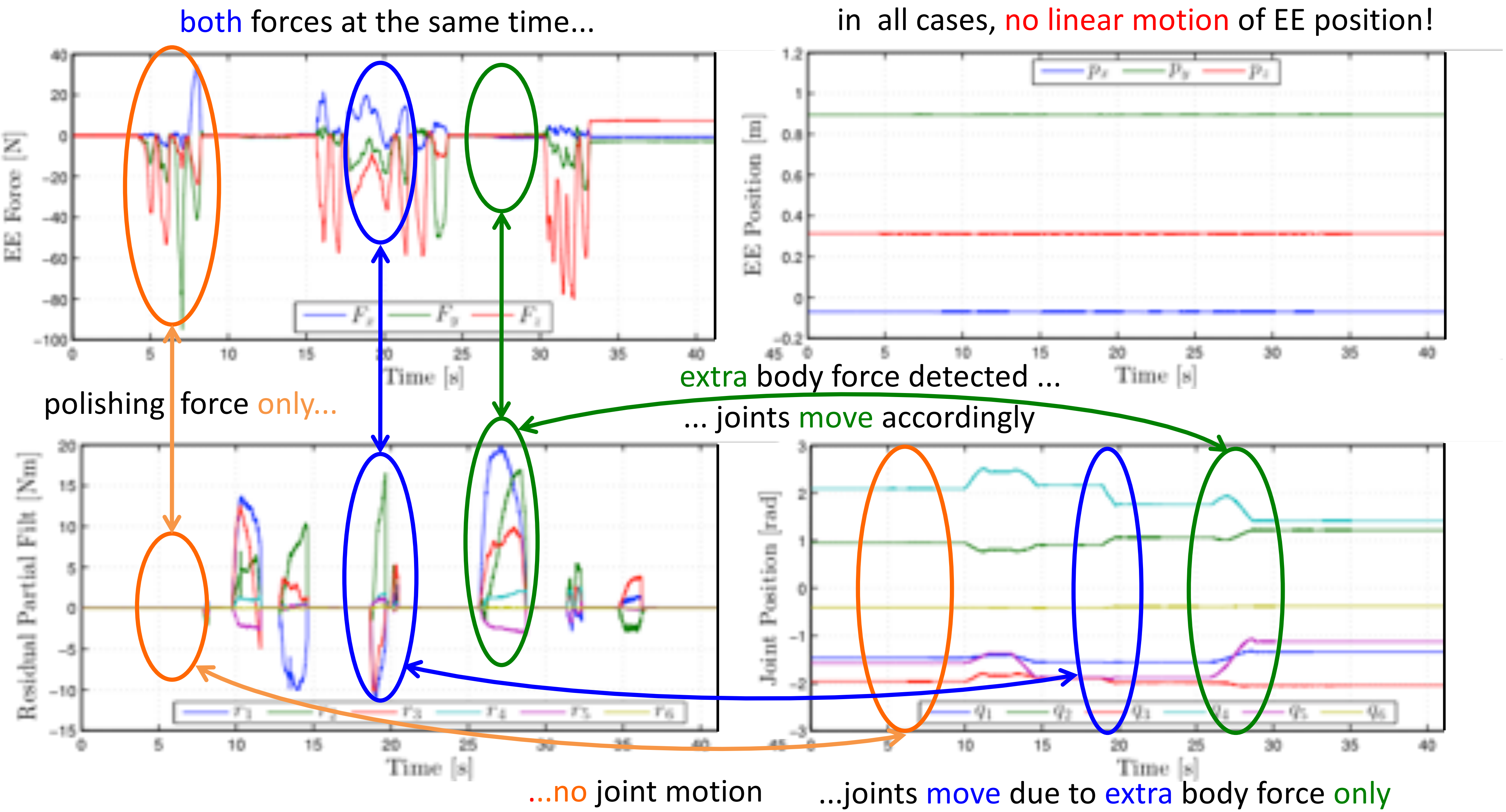
part to be polished



3 videos

HRC phase with UR10 robot

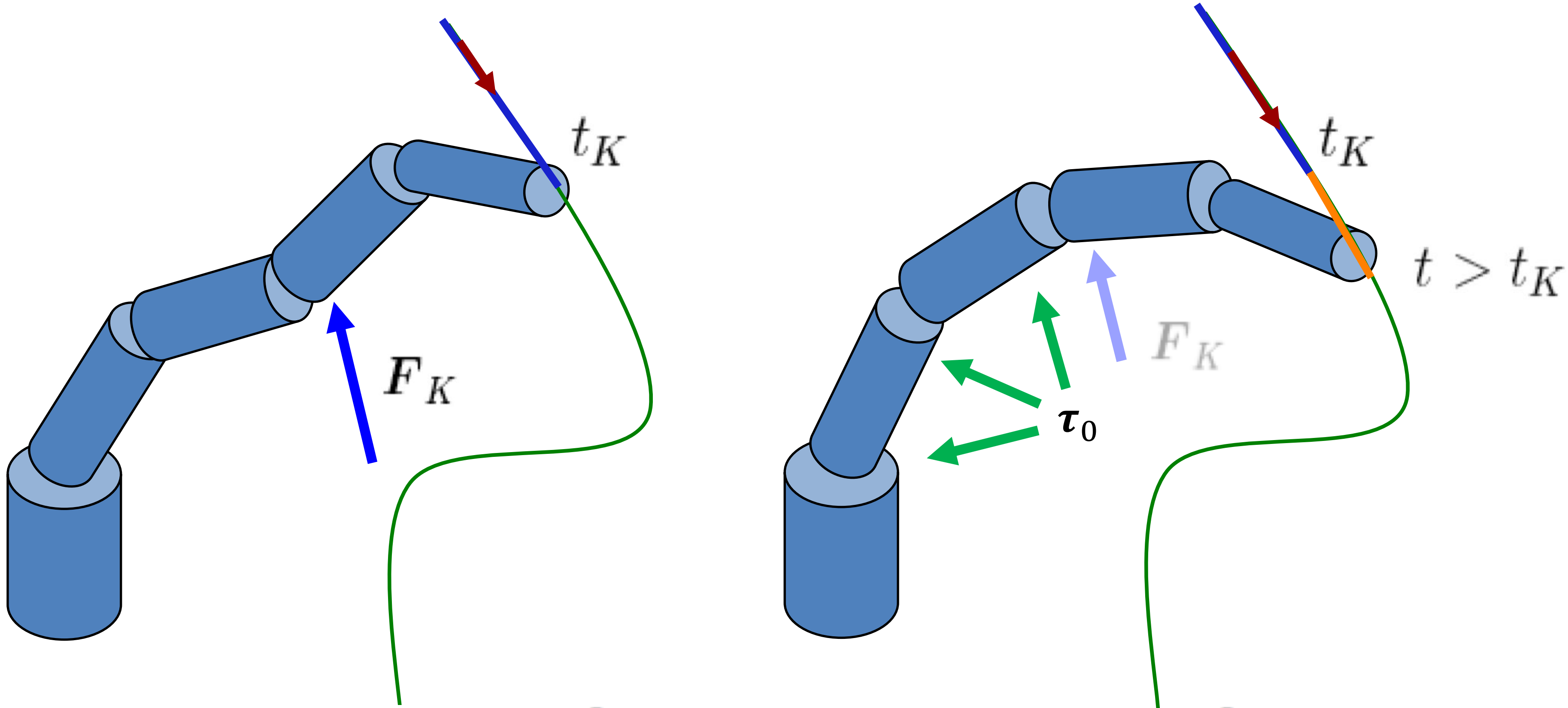
Experimental results (separating F/T measures from residuals)



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

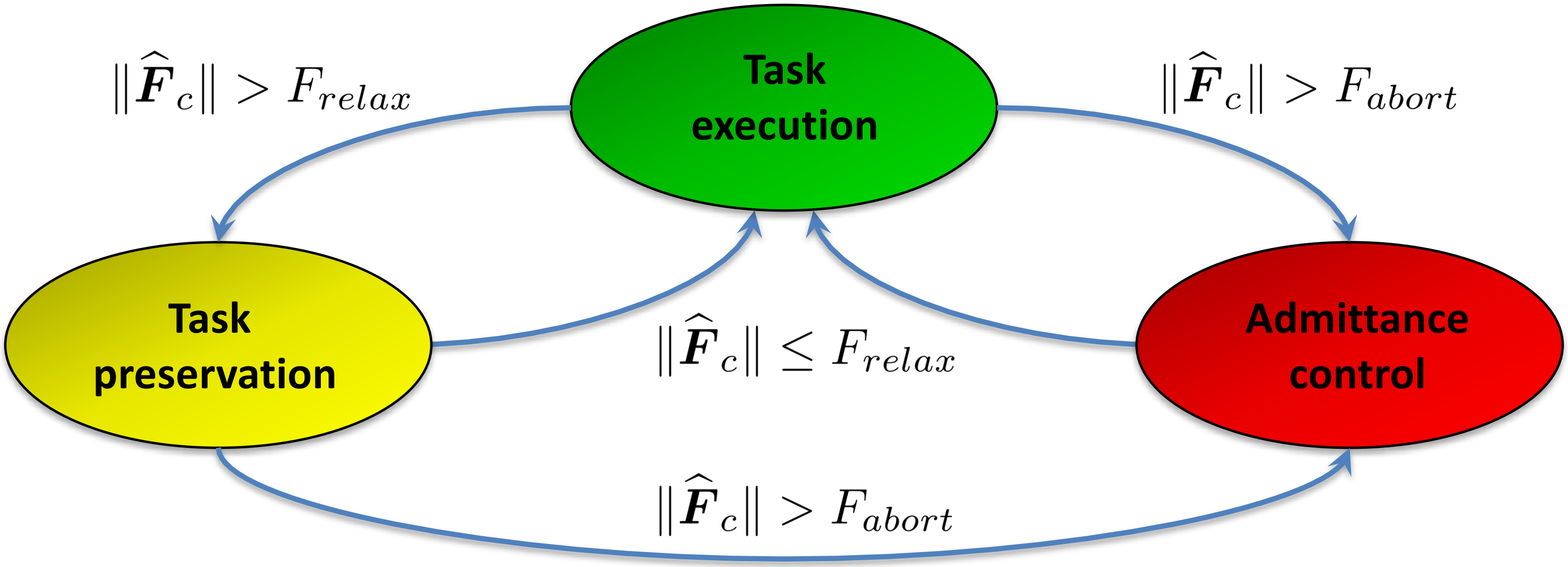


$$\tau = M(q)G(q)\left[\ddot{x} - \dot{J}(q)\dot{q} + J(q)M^{-1}(q)n(q,\dot{q})\right] + M(q)(I - G(q)J(q))M^{-1}(q)\tau_0.$$

Selective reaction to estimated contact force

Robot control strategy (IROS 2008, IROS 2017)

- execution of original end-effector task preserved while reacting to a detected contact, when the **estimated contact force** is above a threshold F_{relax} but is **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 with **admittance control at the contact**



Use of kinematic redundancy

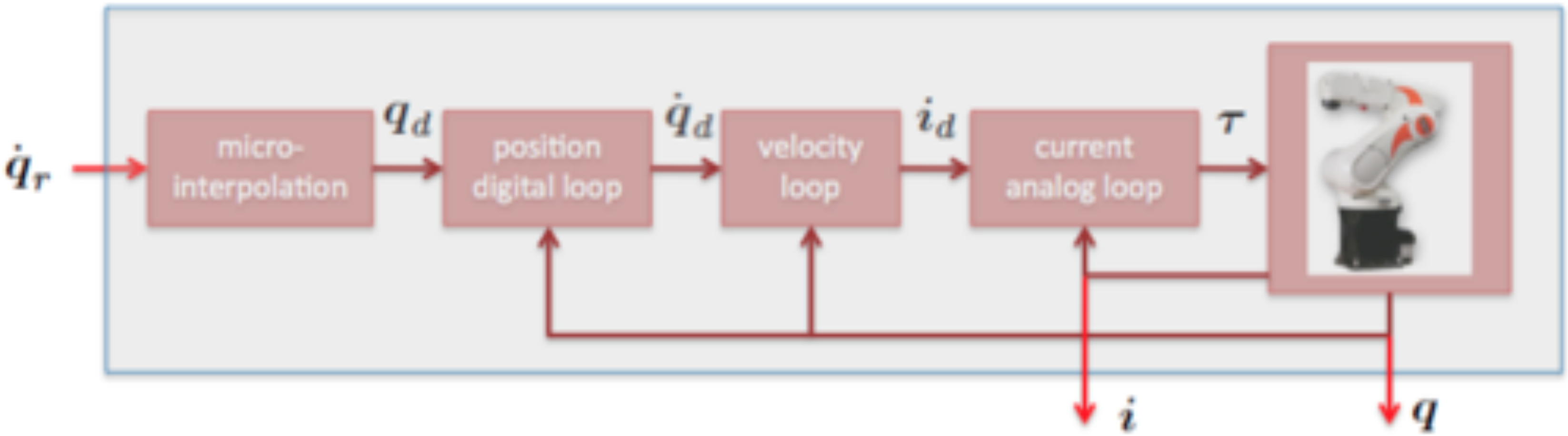
Robot reaction to collisions, in parallel with execution of original task (IROS 2017)

video

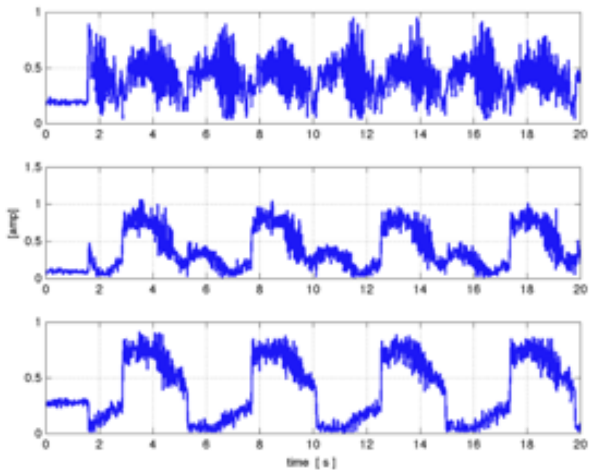
idle ⇔ relax ⇔ abort

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 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 are 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

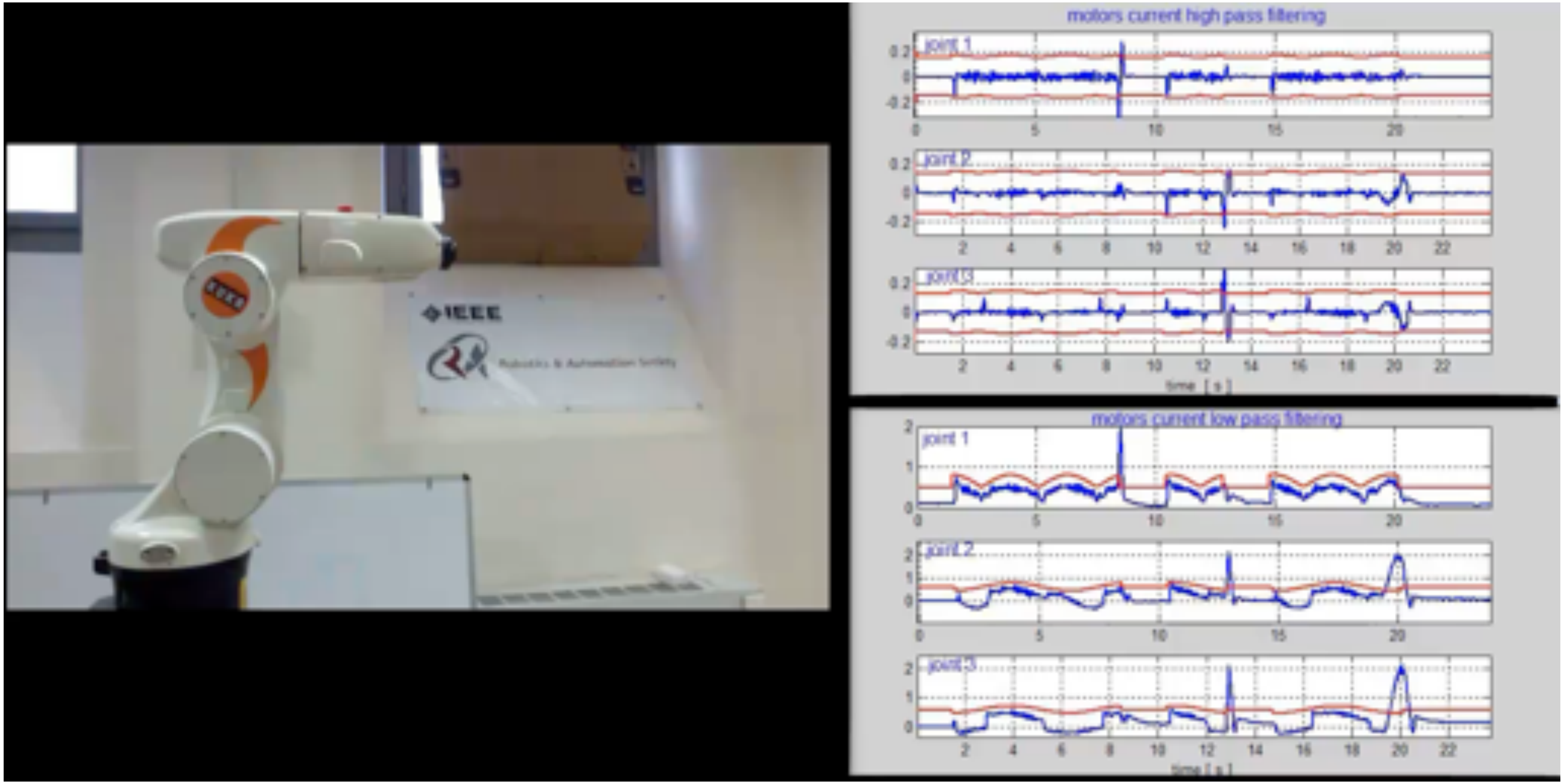


typical motor currents on first three joints

Distinguish accidental collisions from intentional contacts

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

video

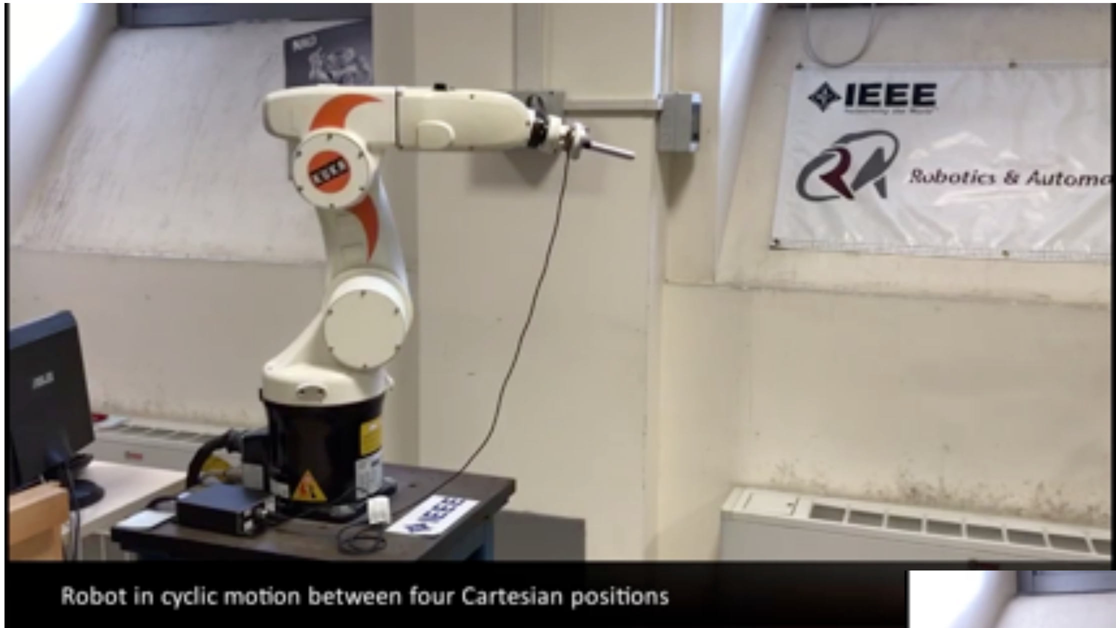


using high-pass and low-pass filtering of motor currents

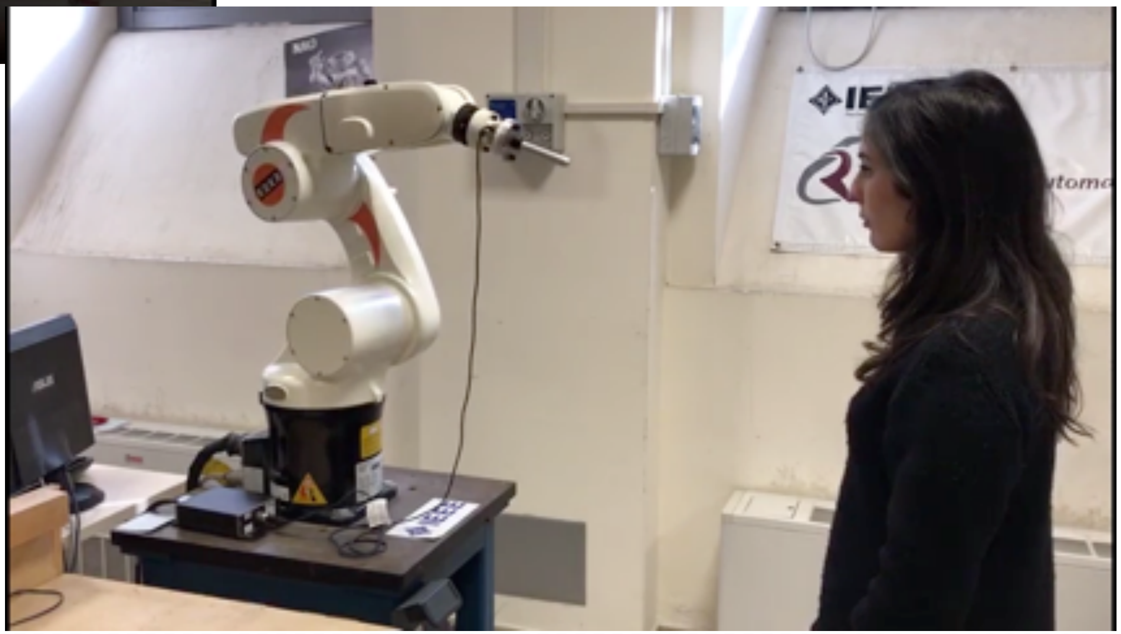
— here collaboration mode is manual guidance of the robot

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 a hierarchy of consistent, **controlled** behaviors of the robot
  - collision detection (and isolation) with model-based residuals
  - portfolio of collision reaction algorithms (using also redundancy)
  - real-time collision avoidance based on data processed in depth space
  - coexistence with visual coordination
  - 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
  - applications are coming from industrial and service stakeholders
  - many interesting research extensions ahead
    - human motion and intention prediction, merging models and data
    - integration with AI-based cognitive HRI modules

Our team at DIAG

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

Acknowledgements

@Sapienza – DIAG - Gabriele Buondonno, Lorenzo Ferrajoli, **Fabrizio Flacco**†, **Claudio Gaz**, Milad Geravand, **Emanuele Magrini**, Eleonora Mariotti, Raffaella Mattone

@DLR – Inst. Robotics and Mechatronics - Alin Albu-Schäffer, Sami Haddadin, Maged Iskandar

@Stanford – AI Lab - Oussama Khatib, Torsten Kröger

References - 1

Download pdf for personal use at www.diag.uniroma1.it/deluca/Publications

- A. De Luca and R. Mattone, "Sensorless robot collision detection and hybrid force/motion control," IEEE Int. Conf. on Robotics and Automation, pp. 999-1004, 2005.
- A. De Luca, A. Albu-Schäffer, S. Haddadin, and G. Hirzinger, "Collision detection and safe reaction with the DLR-III lightweight manipulator arm," IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 1623-1630, 2006.
- S. Haddadin, A. Albu-Schäffer, A. De Luca, and G. Hirzinger, "Collision detection and reaction: A contribution to safe physical human-robot interaction," IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 3356-3363, 2008 (IROS 2008 Best Application Paper Award).
- A. De Luca and L. Ferrajoli, "Exploiting robot redundancy in collision detection and reaction," IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 3299-3305, 2008.
- A. De Santis, B. Siciliano, A. De Luca, A. Bicchi, "An atlas of physical human-robot interaction," Mechanism and Machine Theory, vol. 43, no. 3, pp. 253–270, 2008 (2017 MMT Award for Excellence).
- A. De Luca and L. Ferrajoli, "A modified Newton-Euler method for dynamic computations in robot fault detection and control," IEEE Int. Conf. on Robotics and Automation, pp. 3359-3364, 2009.
- F. Flacco, A. De Luca, "Multiple depth/presence sensors: Integration and optimal placement for human/robot coexistence," IEEE Int. Conf. on Robotics and Automation, pp. 3916-3923, 2010.
- F. Flacco, T. Kröger, A. De Luca, and O. Khatib, "A depth space approach to human-robot collision avoidance," IEEE Int. Conf. on Robotics and Automation, pp. 338-345, 2012.
- A. De Luca and F. Flacco, "Integrated control for pHRI: Collision avoidance, detection, reaction and collaboration," 4th IEEE RAS/EMBS Int. Conf. on Biomedical Robotics and Biomechatronics, pp. 288-295, 2012 (BioRob 2012 RAS Best Paper Award).
- M. Geravand, F. Flacco, and A. De Luca, "Human-robot physical interaction and collaboration using an industrial robot with a closed control architecture," IEEE Int. Conf. on Robotics and Automation, pp. 3985-3992, 2013.
- E. Magrini, F. Flacco, and A. De Luca, "Estimation of contact force using a virtual force sensor," IEEE/RSJ Int. Conf. on Intelligent Robots and System, pp. 2126-2133, 2014.
- F. Flacco, T. Kröger, A. De Luca, and O. Khatib, "A depth space approach for evaluating distance to objects —with application to human-robot collision avoidance," J. of Intelligent & Robotic Systems, vol. 80, suppl. 1, pp. 7-22, 2015.

References - 2

Download pdf for personal use at www.diag.uniroma1.it/deluca/Publications

- E. Magrini, F. Flacco, and A. De Luca, “Control of generalized contact motion and force in physical human-robot interaction,” IEEE Int. Conf. on Robotics and Automation, pp. 2298-2304, 2015 (ICRA 2015 Best Conference Paper Award Finalist).
- E. Magrini and A. De Luca, “Hybrid force/velocity control for physical human-robot collaboration tasks,” IEEE/RSJ Int. Conf. on Intelligent Robots and Systems. pp. 857-863, 2016.
- F. Flacco and A. De Luca, “Real-time computation of distance to dynamic obstacles with multiple depth sensors,” IEEE Robotics and Automation Lett., vol. 2, no. 1, pp. 56-63, 2017.
- M. Khatib, K. Al Khudir, A. De Luca , “ Visual coordination task for human-robot collaboration," IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 3762-3768, 2017
- E. Magrini, A. De Luca, “Human-robot coexistence and contact handling with redundant robots,” IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 4611-4617, 2017.
- S. Haddadin, A. De Luca, and A. Albu-Schäffer, “Robot collisions: A survey on detection, isolation, and identification,” IEEE Trans. on Robotics, vol. 33, no. 6, pp. 1292-1312, 2017.
- C. Gaz, A. De Luca, “Payload estimation based on identified coefficients of robot dynamics --with an application to collision detection, ” IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp. 3033-3040, 2017.
- C. Gaz, E. Magrini, A. De Luca “ A model-based residual approach for human-robot collaboration during manual polishing operations,” Mechatronics, vol. 55, pp. 234-247, 2018.
- E. Mariotti, E. Magrini, A. De Luca, “Admittance control for human-robot interaction using an industrial robot equipped with a F/T sensor,” IEEE Int. Conf. on Robotics and Automation, pp. 6130-6136, 2019.
- M. Khatib, K. Al Khudir, A. De Luca, “ Human-robot contactless collaboration with mixed reality interface," Robotics and Computer-Integrated Manufacturing, vol. 67, 102030, 2021.
- M. Iskandar, O. Eiberger, A. Albu-Schäffer, A. De Luca, A. Dietrich, “Collision detection and localization for the DLR SARA robot with sensing redundancy,” IEEE Int. Conf. on Robotics and Automation, 2021 (ICRA 2021 Best HRI Paper Award Finalist).

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