1st Doctoral Summer School
on Intelligent Robots and Machines (DRIMS2)
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On the Control of Physical Human-Robot Interaction

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SAPIENZA UNIVERSITÀ DI ROMA

Summary

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

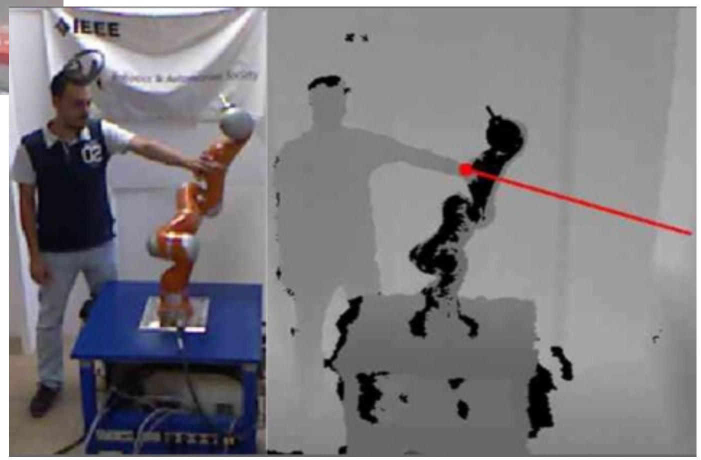
- Safe control of physical Human-Robot Interaction/Collaboration (pHRI/HRC)
  - safety standards, types of collaborative operation, and control architecture
- Coexistence
  - human and robot actively sharing the same workspace
  - coordinated actions without contacts
- Safety
  - detecting/isolating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

Basic safety-related control problems in pHRI

Handling of collisions and intentional contacts

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

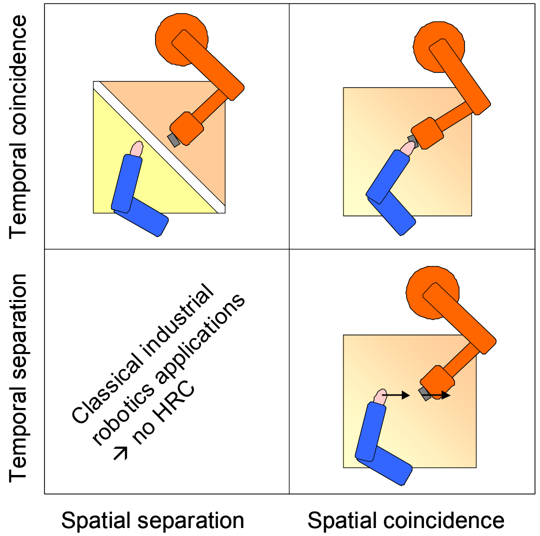
workspace monitoring
for **continuous**
collision avoidance
(while the task is running)



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

Human-robot collaborative operation

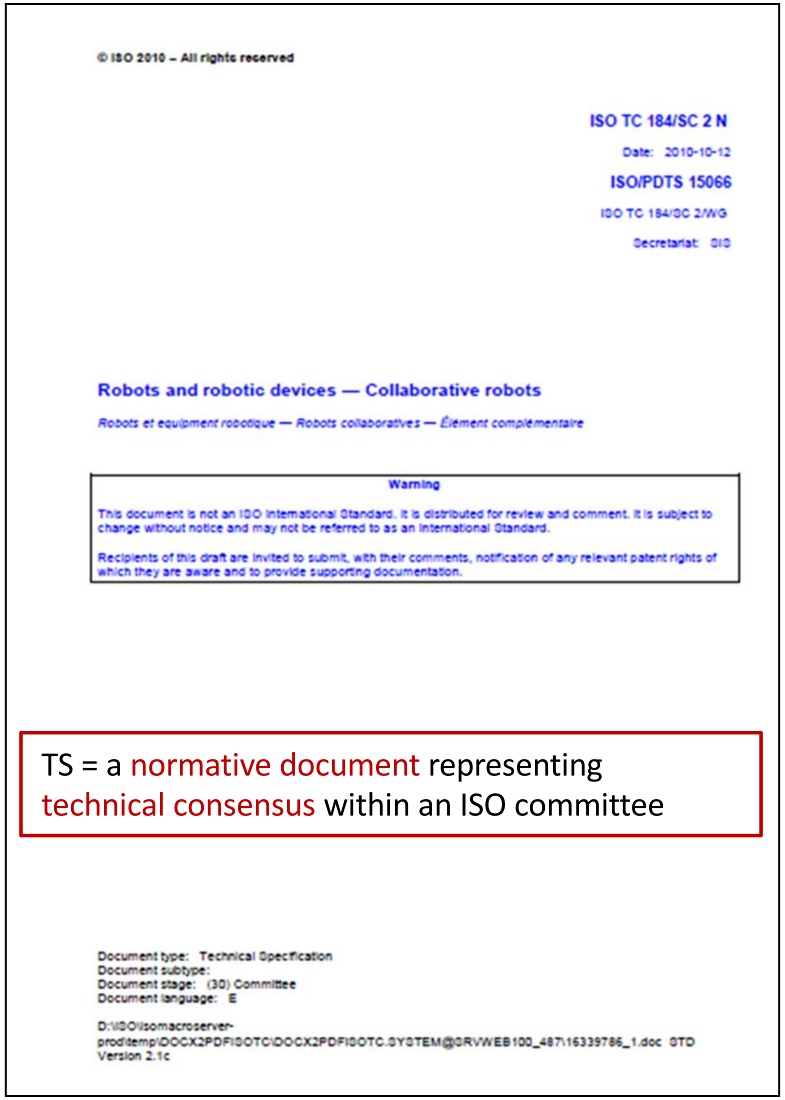
Definition according to the current standard ISO 10218



- ISO 10218-1:2011, clause 3.4
  - ***collaborative operation***
    state in which purposely designed robots work in direct cooperation with a human within a defined workspace
- Degree of collaboration
  1. Once for setting up
     (e.g. lead-through teaching)
  2. Recurring isolated steps
     (e.g. manual gripper tending)
  3. Regularly or continuously
     (e.g. manual guidance)

ISO/TS Technical Specification 15066

Complements ISO 10218 standard



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ISO TC 184/SC 2 N
Date: 2010-10-12
ISO/PDTS 15066
ISO TC 184/SC 2/WG
Secretariat: SIS

Robots and robotic devices — Collaborative robots

Robots et equipment robotique — Robots collaboratives — Élément complémentaire

Warning

This document is not an ISO International Standard. It is distributed for review and comment. It is subject to change without notice and may not be referred to as an International Standard.

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Document type: Technical Specification
Document subtype:
Document stage: (30) Committee
Document language: E

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TS = a normative document representing technical consensus within an ISO committee

for collaborative robots

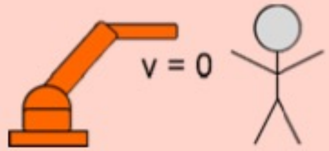
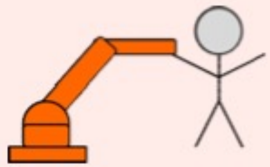
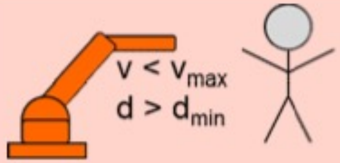
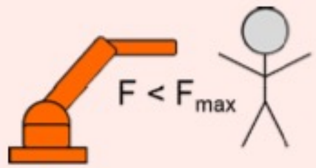
- Design of collaborative work space
- Design of collaborative operation
  - Minimum separation distance S / maximum robot speed K_R
  - Static (worst case) or dynamic (continuously computed) limit values
  - Safety-rated sensing capabilities
  - Ergonomics
- Methods of collaborative working
  - Safety-rated monitored stop
  - Hand-guiding
  - Speed and separation monitoring
  - Power and force limiting (biomechanical criteria!)
- Changing between
  - Collaborative / non-collaborative
  - Different methods of collaboration
- Operator controls for different methods, applications
  - Question is subject of debate: What if a robot is purely collaborative? Must it fulfill all of ISO 10218-1, i.e. also have mode selector, auto / manual mode, etc.?

latest version … :2016

(reviewed and confirmed as such in 2019)

Types of collaborative operation

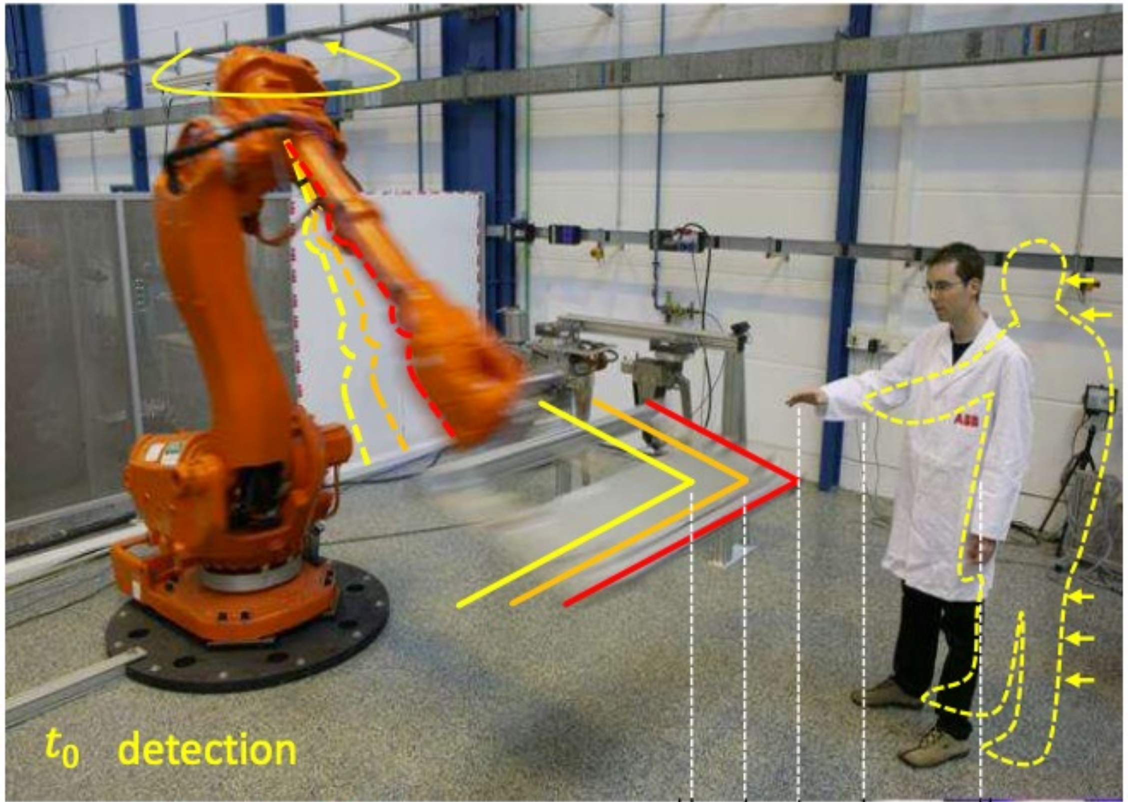
According to ISO 10218-1, ISO/TS 15066

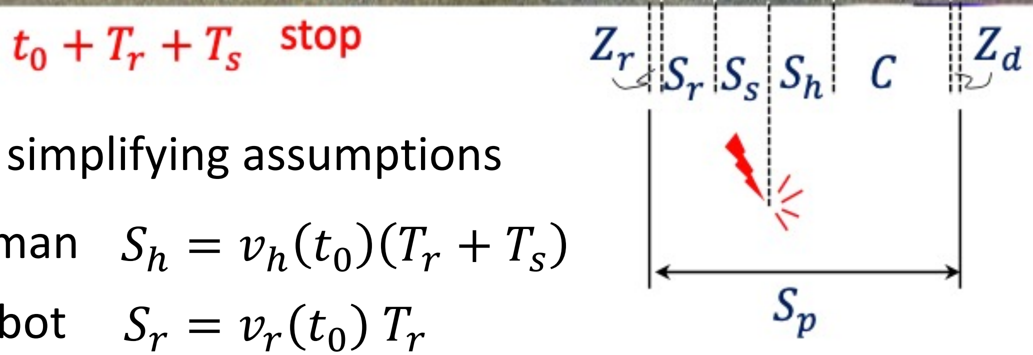
ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	
5.10.2	Safety-rated monitored stop (Example: manual loading-station)	No robot motion when operator is in collaborative work space	
5.10.3	Hand guiding (Example: operation as assist device)	Robot motion only through direct input of operator	
5.10.4	Speed and separation monitoring (Example: replenishing parts containers)	Robot motion only when separation distance above minimum separation distance	
5.10.5	Power and force limiting by inherent design or control (Example: *ABB YuMi®* collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

[courtesy of ABB]

Speed and separation monitoring

Worst case analysis: human and robot moving against each other





simplifying assumptions

human $S_h = v_h(t_0)(T_r + T_s)$

robot $S_r = v_r(t_0)\, T_r$

protective separation **distance S_p**

space travelled by/due to …

robot before reaction	robot during stopping	human in the meantime

$$S_p = S_r + S_s + S_h + Z_r + C + Z_d$$

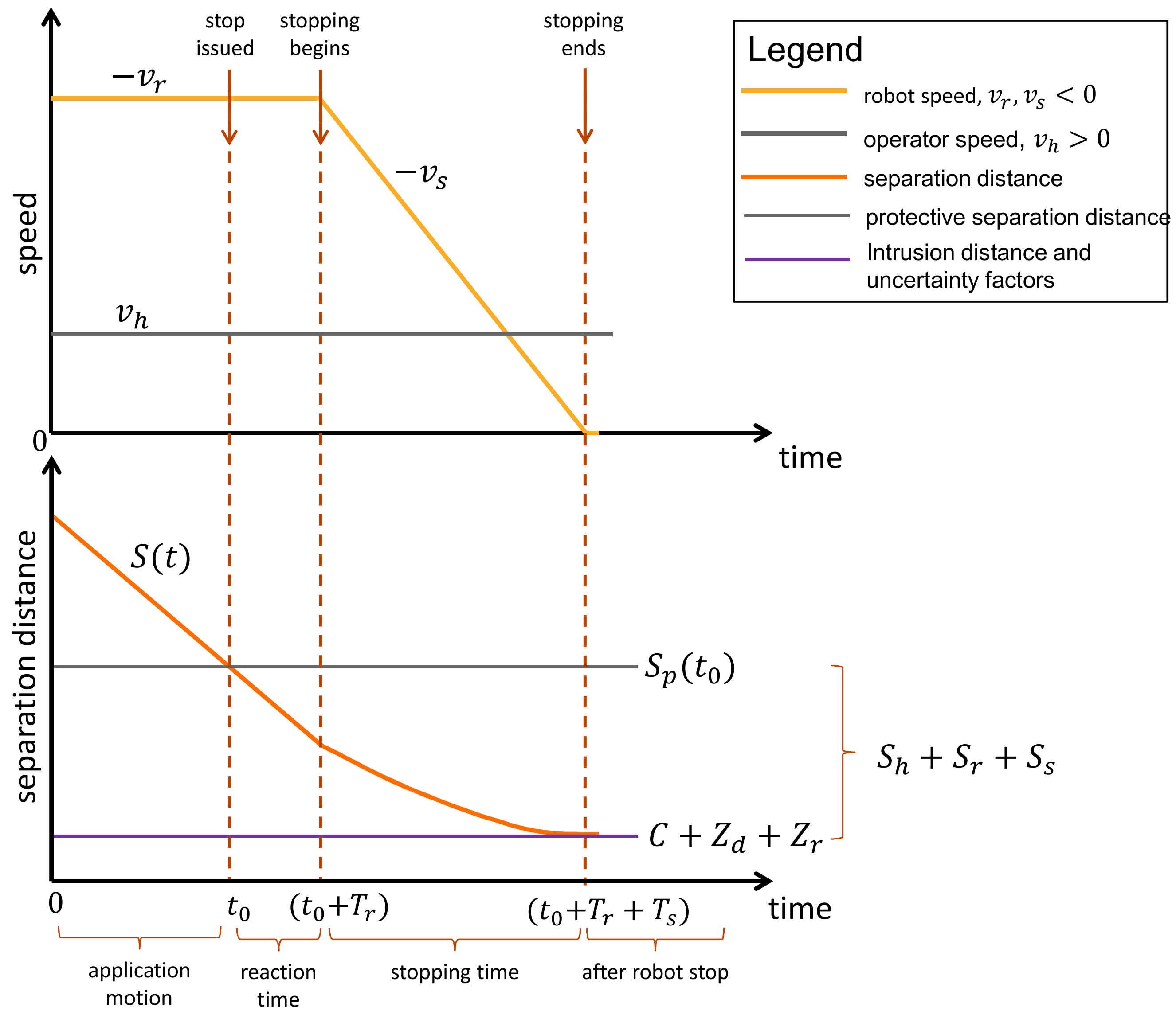
uncertainty robot sensors	intrusion distance (ISO 13855)	uncertainty distance sensors

condition for sufficient protection at time t_0

$$S_{measured}(t_0) \geq S_p(t_0)$$

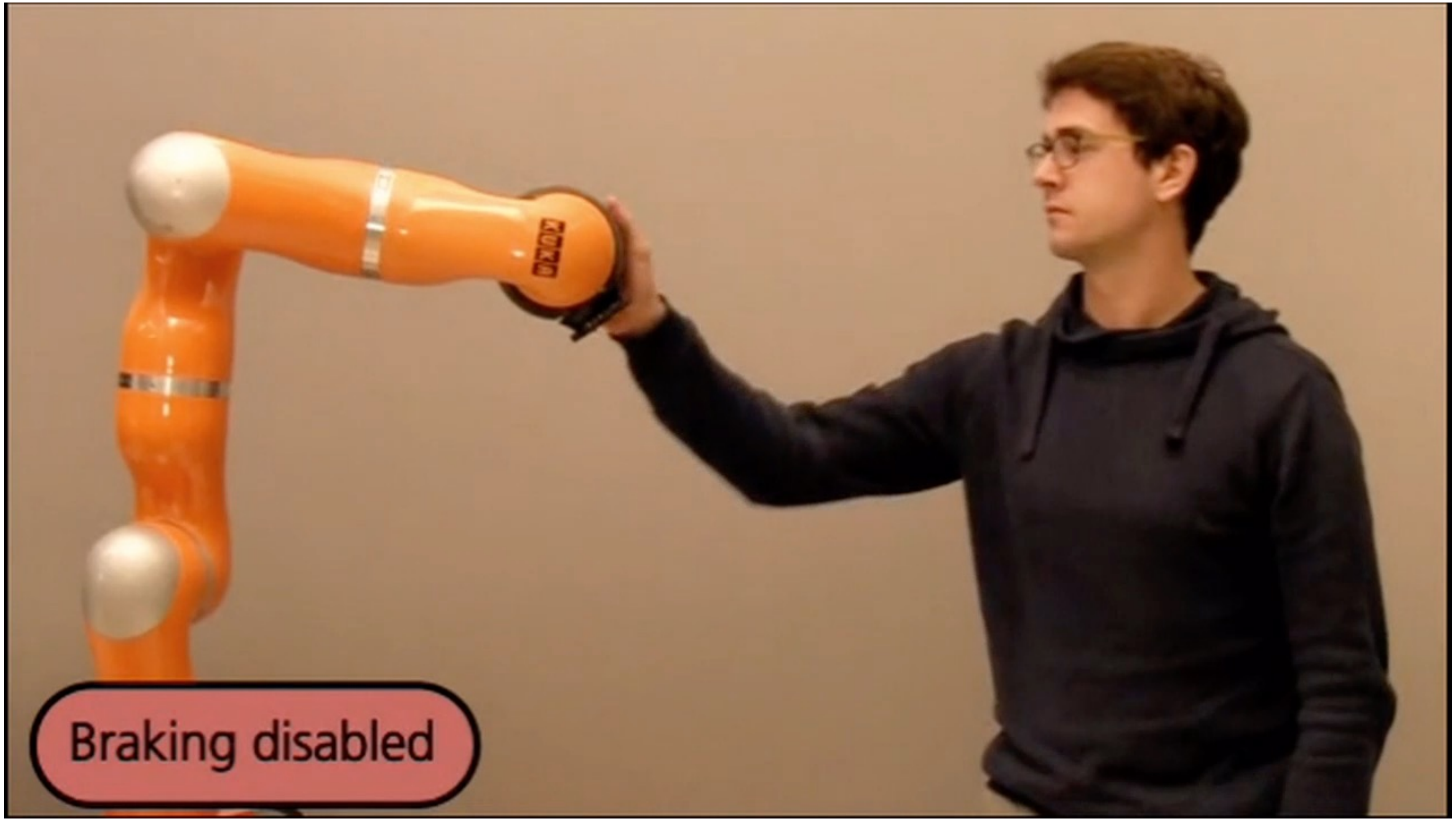
Speed and separation monitoring

Worst case analysis: human and robot moving against each other



Stopping an LWR arm

Considering its joint compliance

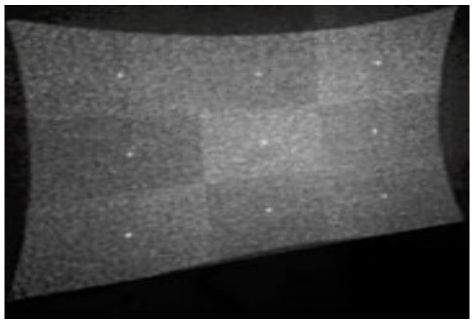


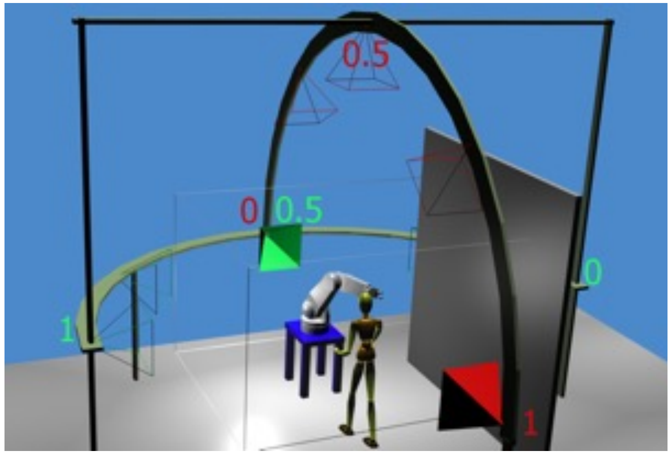
video [Nico Mansfeld, DLR]

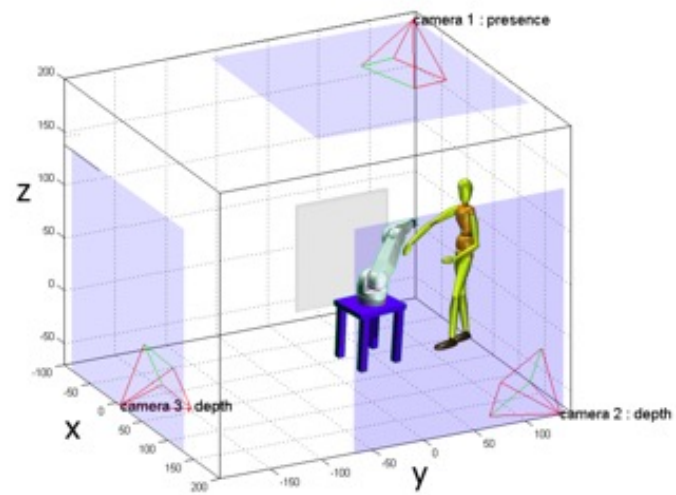
Collision avoidance

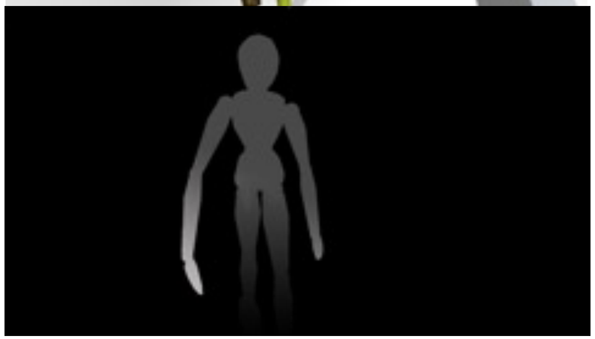
Using exteroceptive sensors to monitor robot workspace (ICRA 2010)

- **external sensing:** stereo-camera, TOF, structured light, depth, laser, presence, ... placed optimally to minimize occlusions (robot can be removed from images)









Safe human-robot coexistence

Industrial solutions usually waste free space and/or time

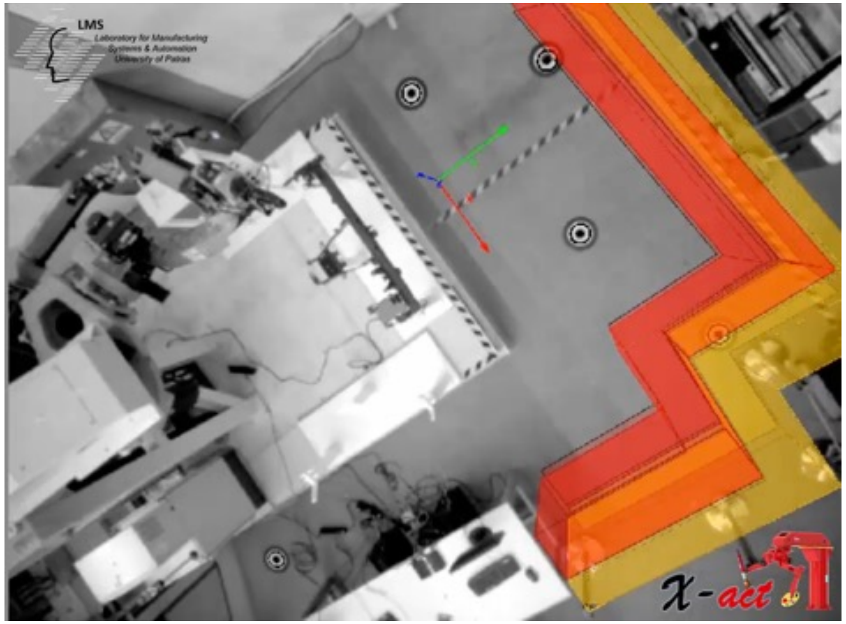
https://youtu.be/2ad_ol_4eJ8

video

commercial video by **ABB Robotics**
with SafeMove2 software
using 2 laser scanners [2016]

use of Pilz SafetyEye with
definition of safety zones
in FP7 EU project **X-act** [2015]

video



https://youtu.be/_MVruSKhpHA

Safe human-robot coexistence

Many solutions were intended only for occasional proximity

by evaluating in real-time the **severity of a possible collision MeRLIn @PoliMI)** [2014]

- protective stop
- evasive motion
- speed reduction
- no special action

3-part video

https://youtu.be/dVVvoxDDkT8

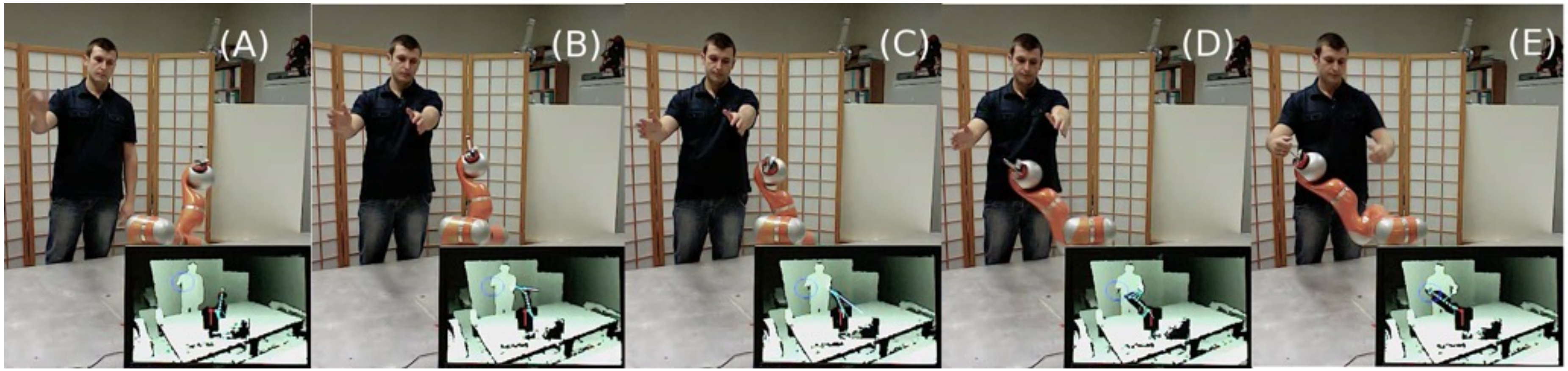
A control architecture for physical HRI

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**)

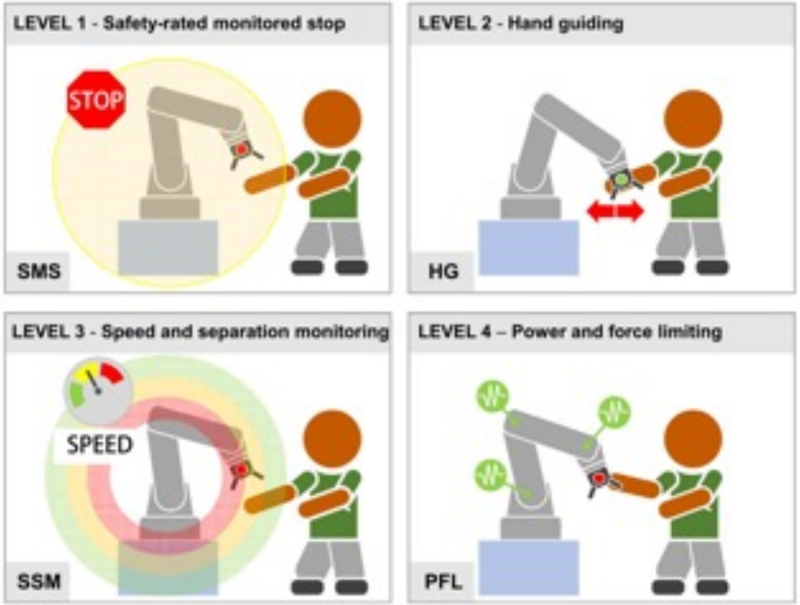
Coexistence is the robot capability of sharing the workspace with humans (**collision avoidance**)

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



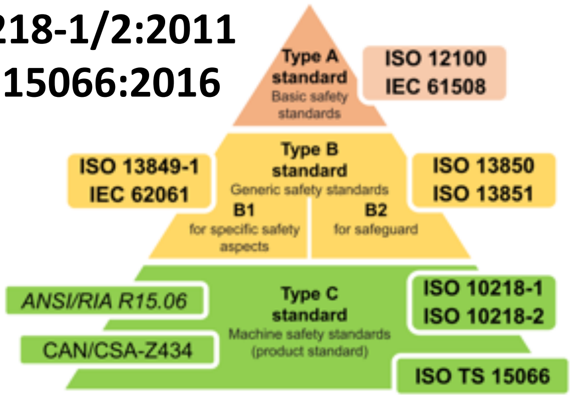
A control architecture for physical HRI

Relation with ISO Standard 10218 and Technical Specification 15066



SAFETY	Speed	Separation distance	Torques	Operator controls	Main risk reduction
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

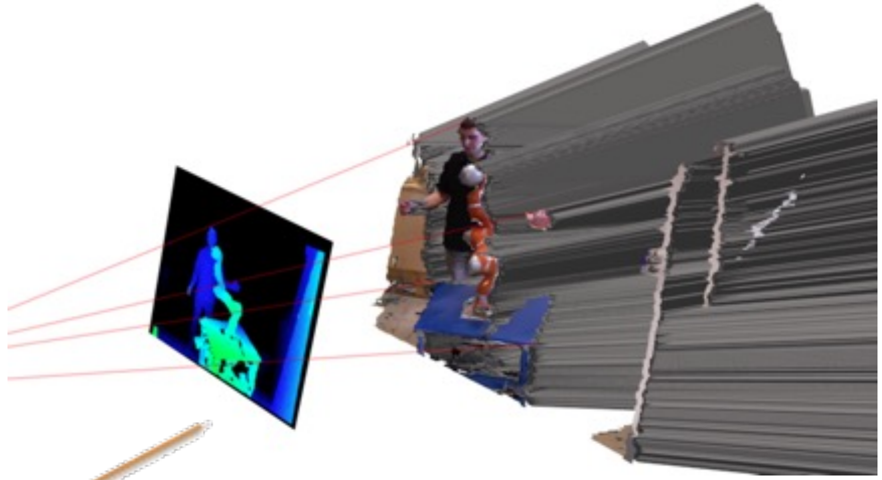
Collision avoidance working in depth space

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

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

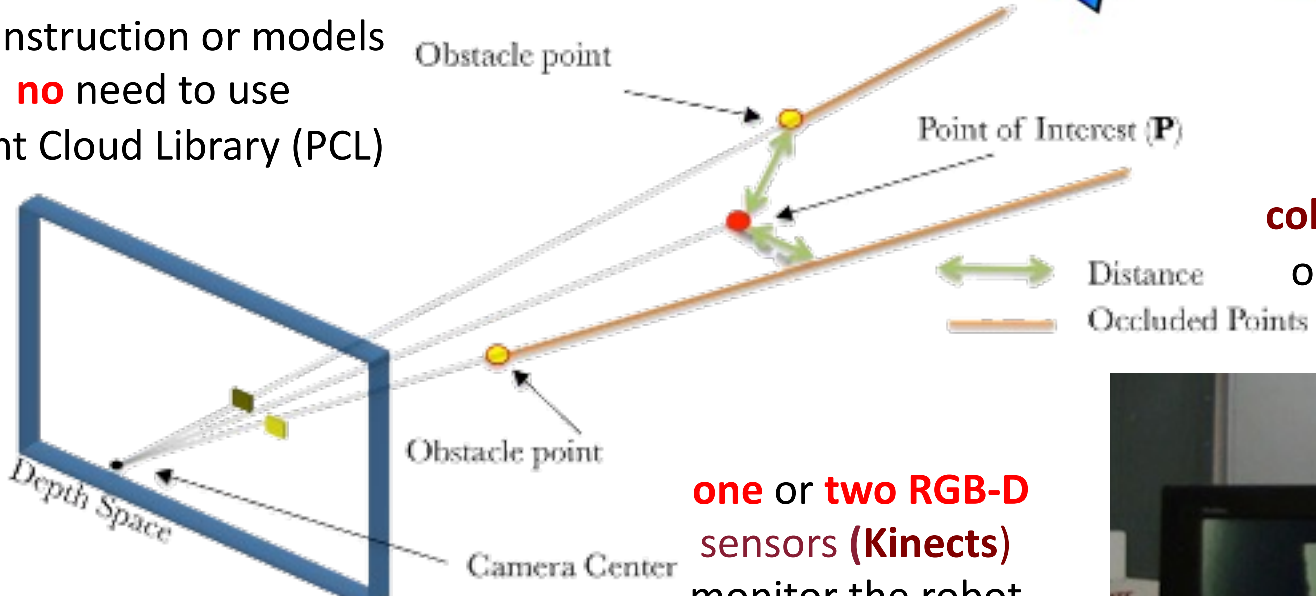
$$p_y = \frac{y_C f s_y}{z_C} + c_y$$

$$d_p = z_C$$



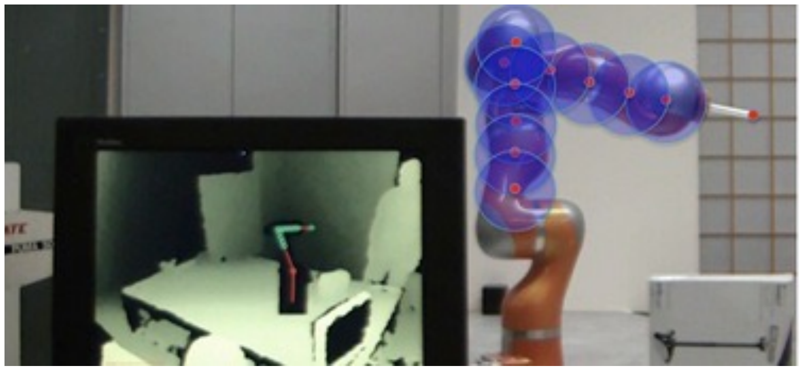
gray areas behind obstacles

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

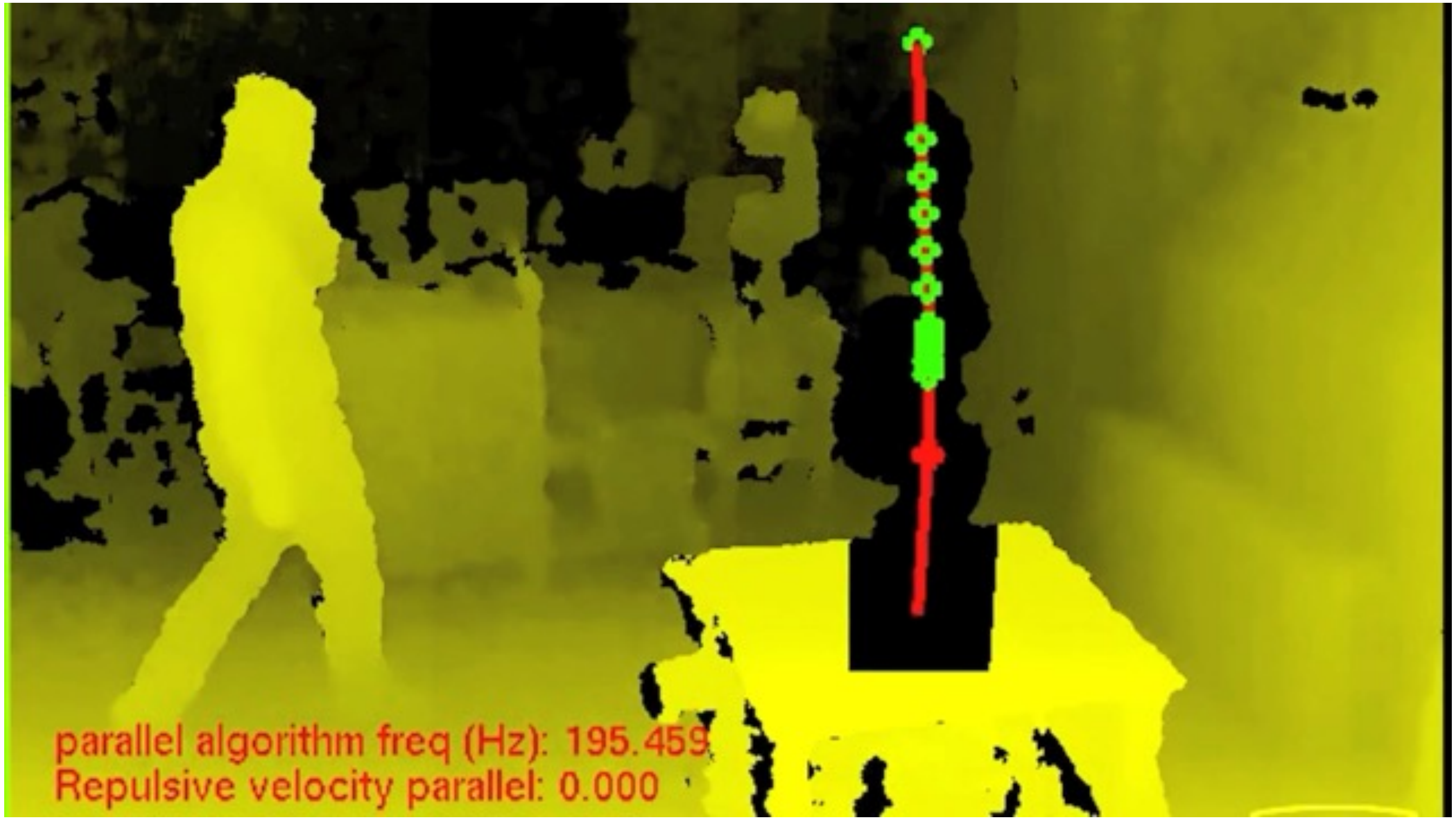


[see also the video https://youtu.be/iapfbAfklw4]

Safe human-robot coexistence

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

video https://youtu.be/pIlhY8E3HFg

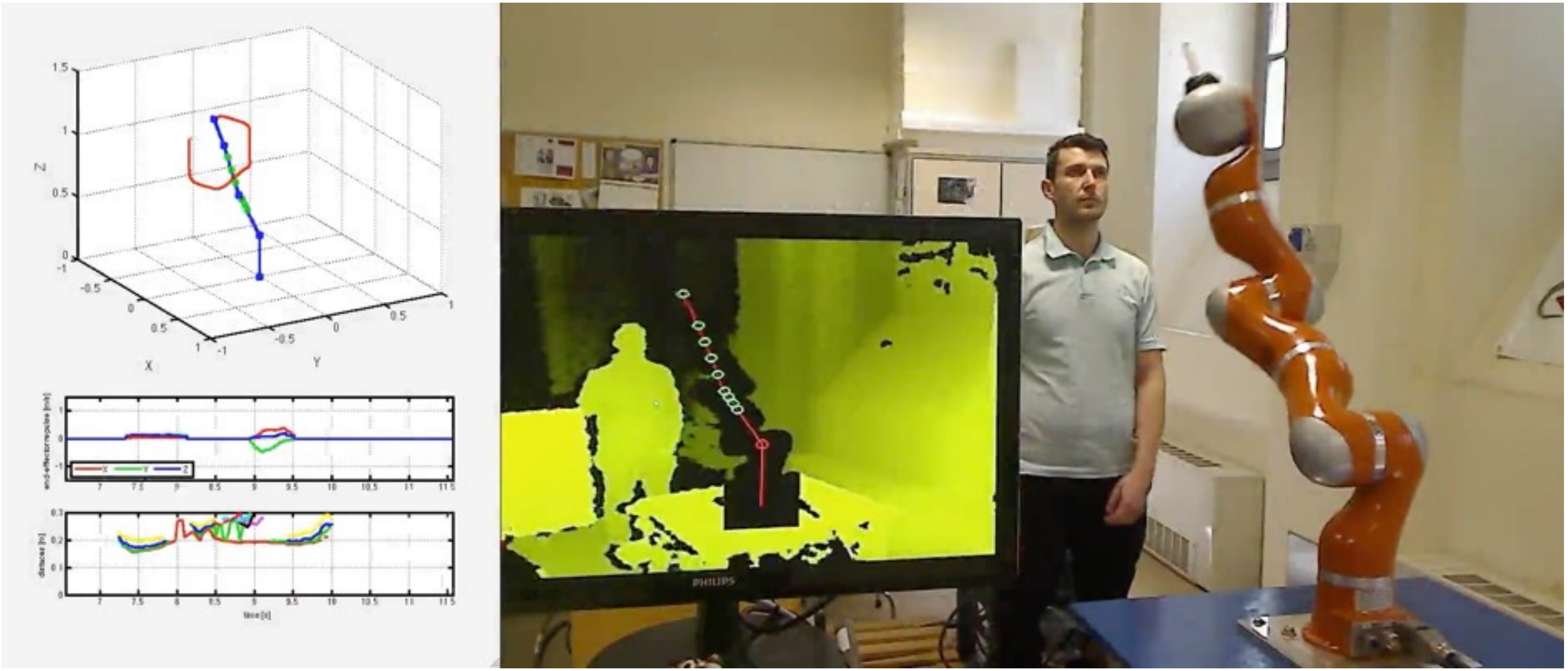


- **distances** between robot [control] points and obstacles in **depth space** at 300Hz
- **coexistence** through standard collision avoidance algorithms

Safe human-robot coexistence

Collision avoidance in depth space (J. Intell. & Rob. Syst. 2015)

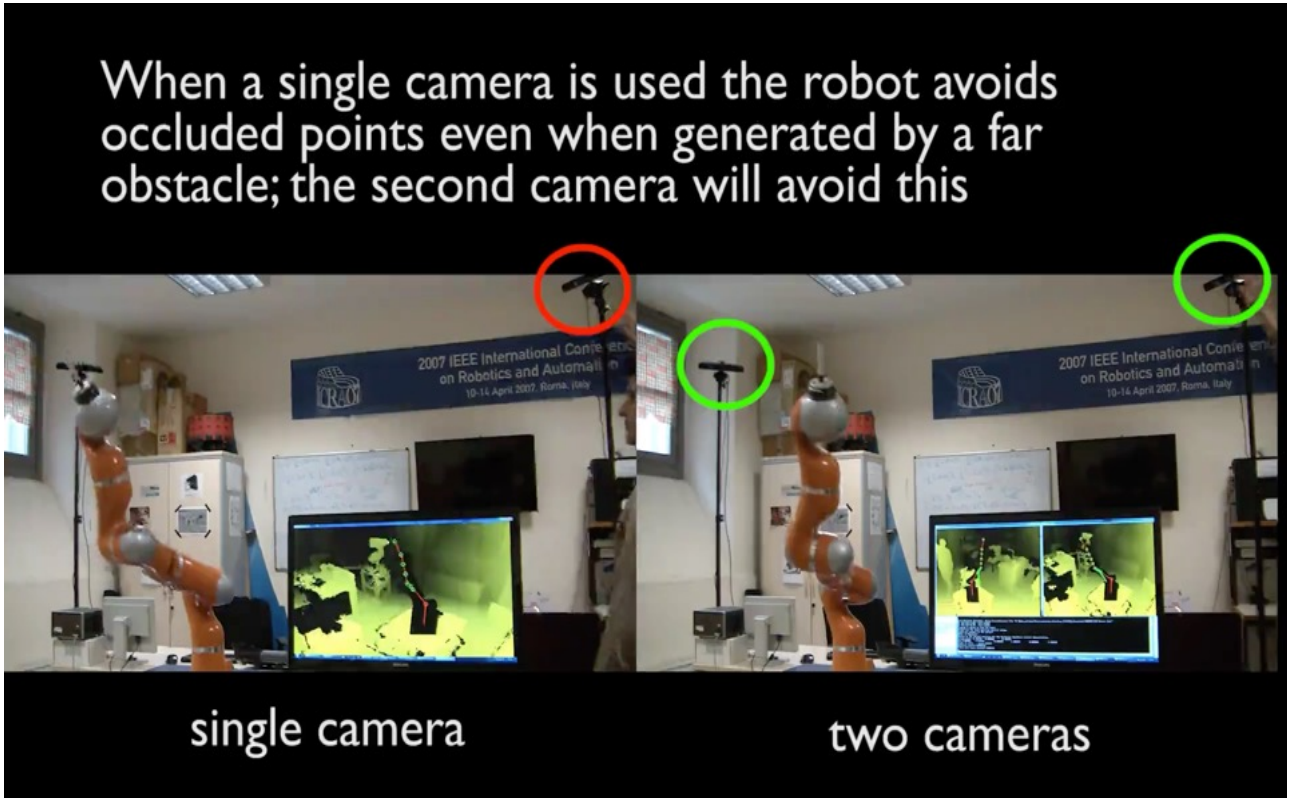
video https://youtu.be/iapfbAfklw4



- **resuming** a planned cyclic Cartesian **task** as soon as possible …

Monitoring workspace with two Kinects

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



video
https://youtu.be/WIw_Uj_ooYI

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

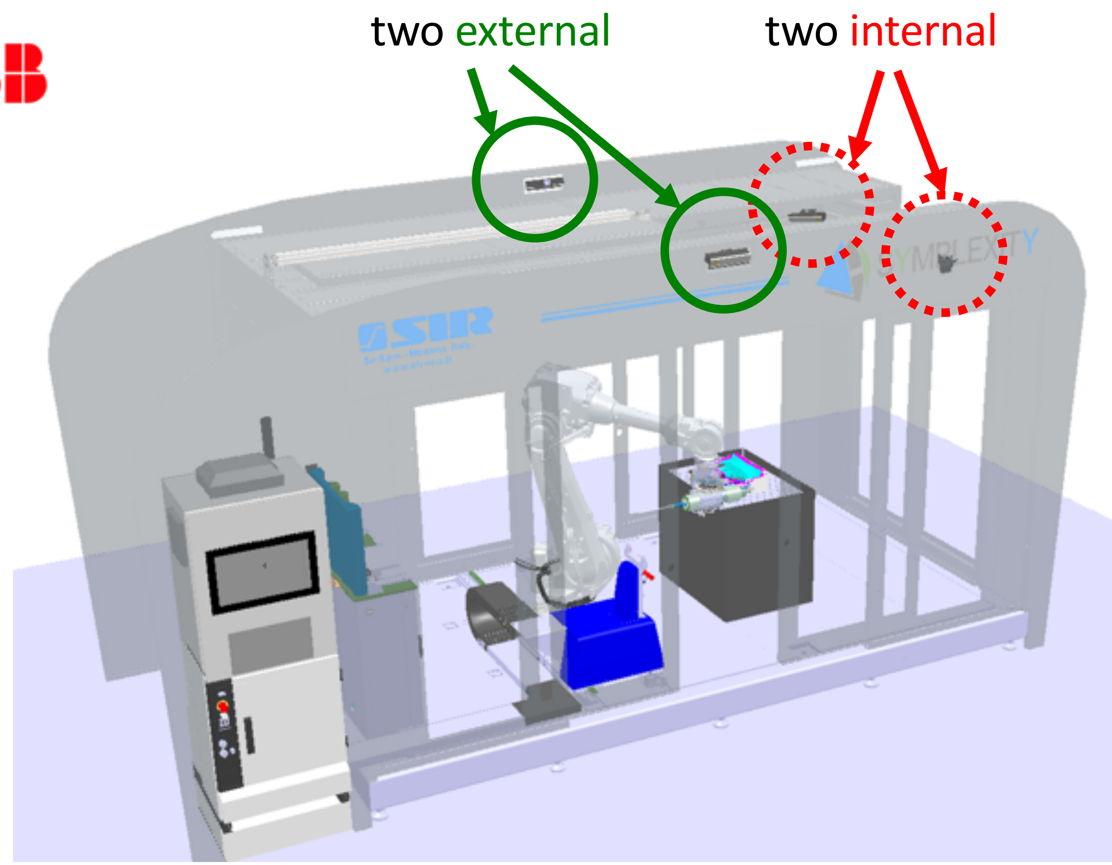
+ eliminates collision with false, far away "shadow" obstacles
+ reduces to a minimum gray areas, thus detects what is "behind" the robot
+ calibration is done once off-line

SYMPLEXITY cell for robotized work on metallic surfaces

For abrasive finishing/fluid jet polishing tasks & for human-robot quality assessment

SYMPLEXITY **H2020 FoF EU project (2015-18)**

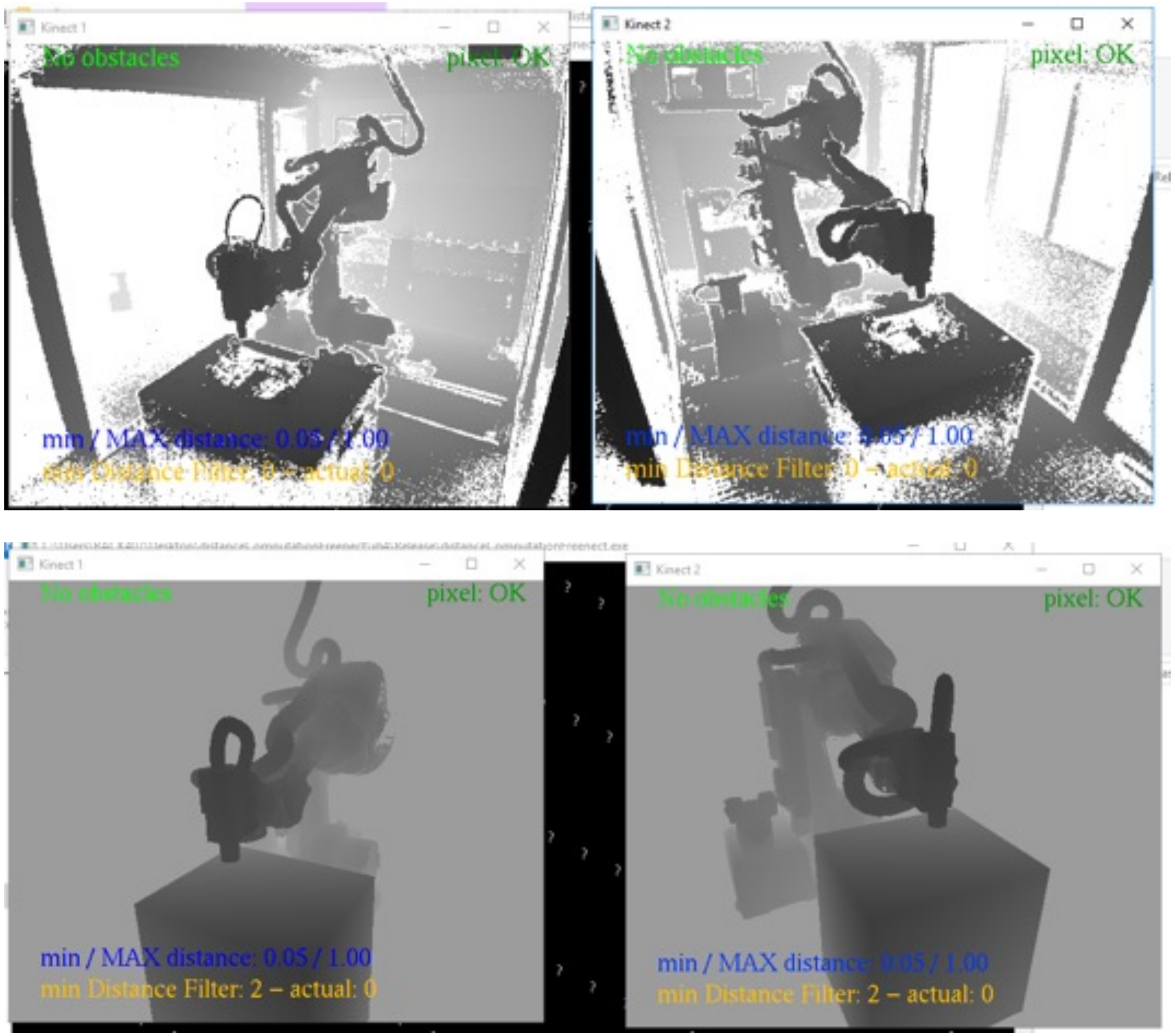
- ABB IRB 4600-60 robot, with integrated SafeMove option
- certified communication with cell PLC, using ProfiSAFE protocol
- due to the intrinsic risks in the technological process, only for **HR coexistence** during visual check and measuring phase or for **contactless collaboration**
- **2 external** Kinects to recognize human gestures (e.g., automatic door opening, …)
- **2 internal** Kinects (placed at the top corners of the cabin) for monitoring human-robot distances

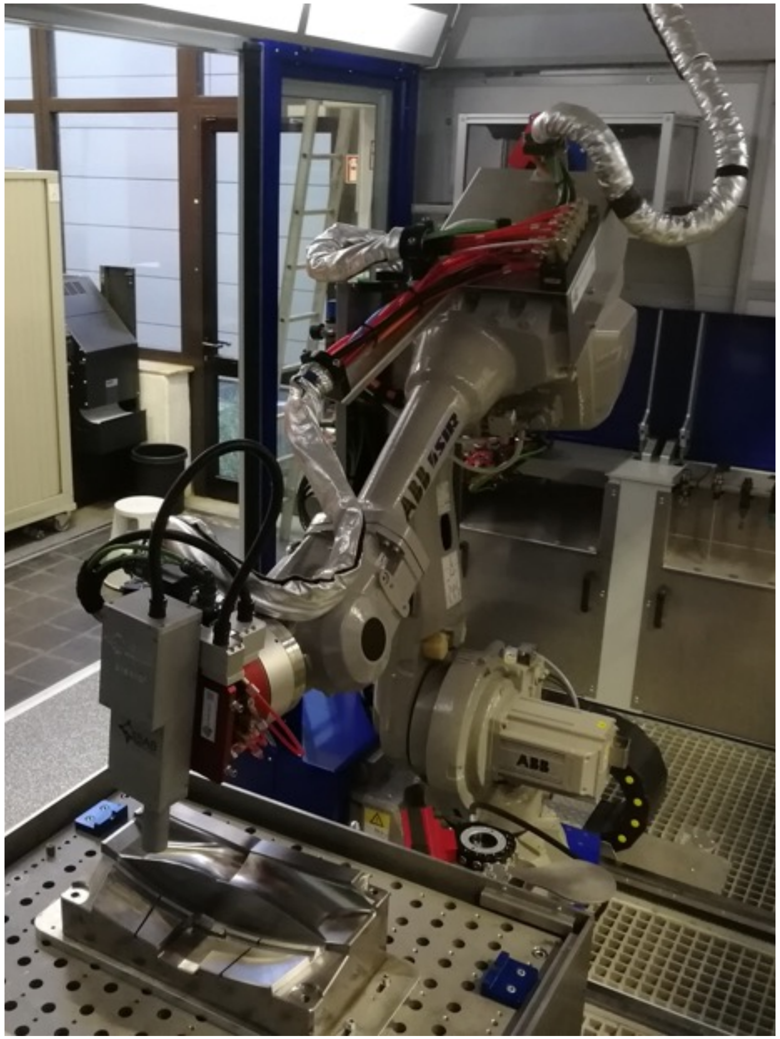


SIR ROBOTIC SOLUTIONS | UNIMORE UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA | SAPIENZA UNIVERSITÀ DI ROMA

CAD model of the robot and equipments/tools/cables

Filtering out the right parts from the depth images

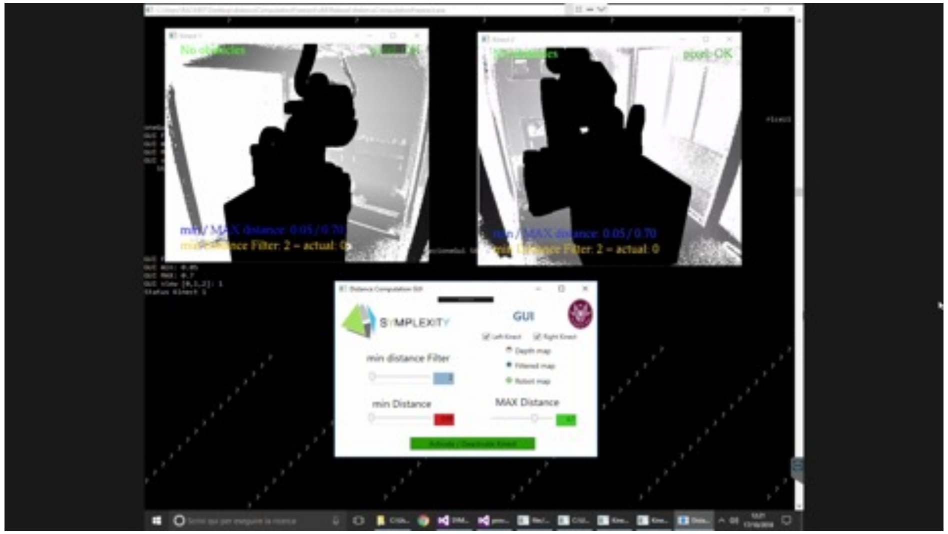




Safe coexistence in an industrial robotic cell

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

2 simultaneous videos



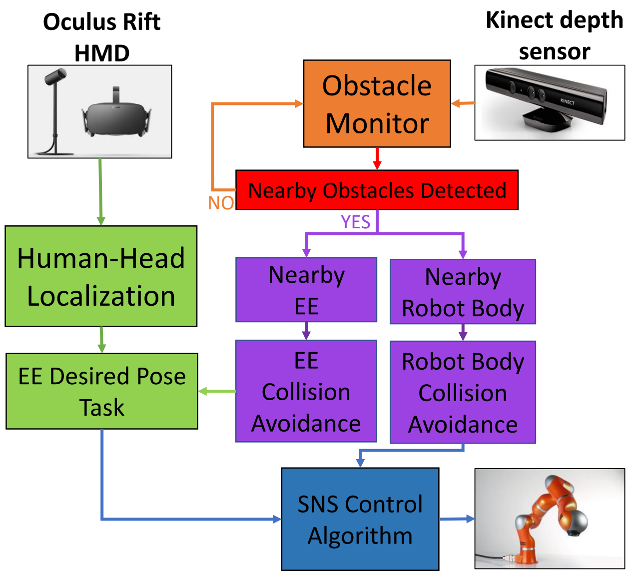
depth images and GUI

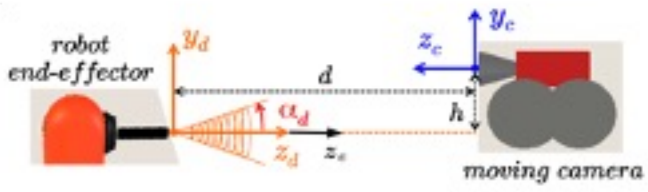
- the robot is moving at max 100 mm/s
- no safety zones were defined in the ABB SafeMove software
- need a risk analysis & a mitigation plan on the two Kinects data and algorithm
  - e.g., when the view of one camera is obstructed, safety-certified laser sensors are used instead to estimate human distance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

[see also the video https://youtu.be/qa8lOu9ymLg]

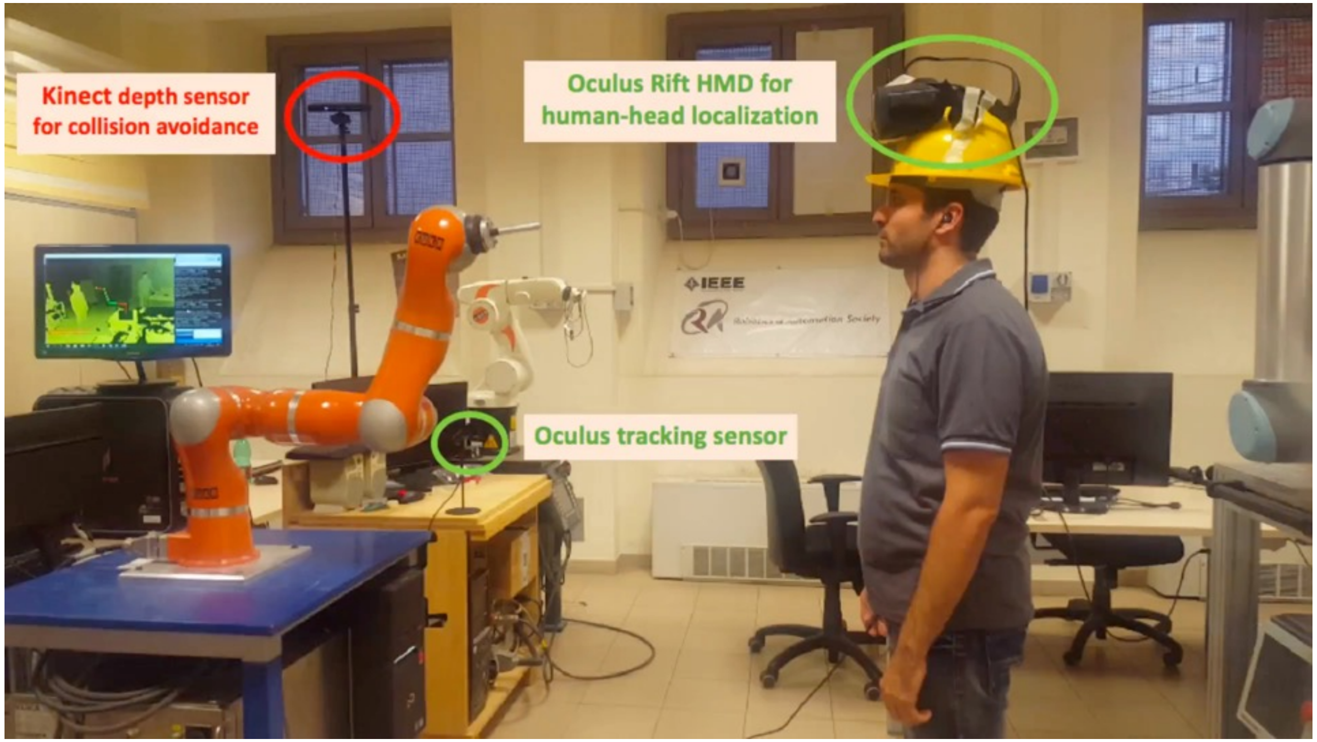
Coexistence with visual coordination

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





video https://youtu.be/SRfpNrZD7k0



position error
≤ 5 cm

pointing error
< 0.03 rad

- 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

Visual coordination with Augmented Reality

Multi-sensory operation with collision avoidance

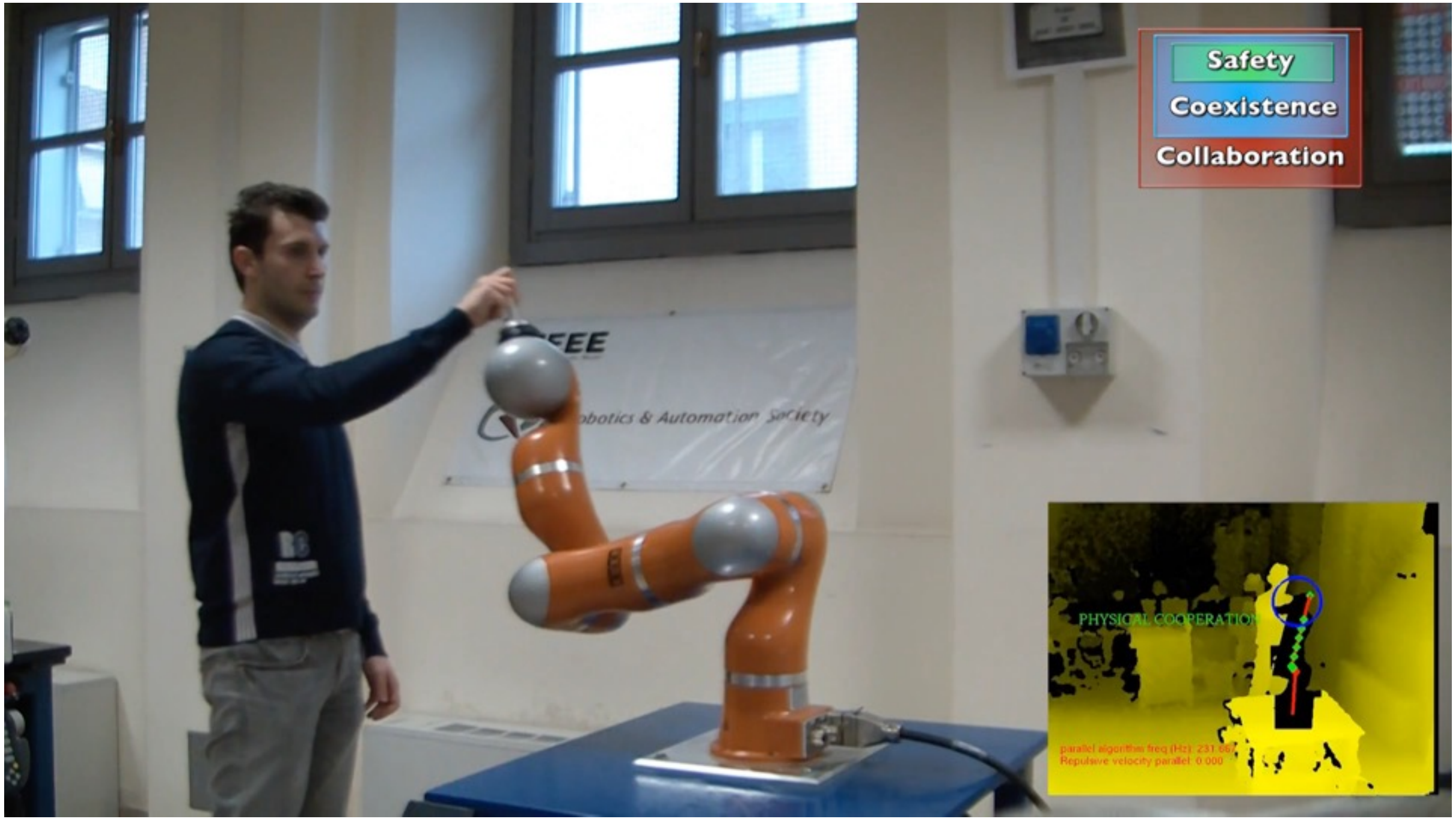
video https://youtu.be/qa8lOu9ymLg

Robotics and Computer-Integrated Manufacturing, 2021

Safe coexistence and collaboration

Second part of finalist video at IROS 2013

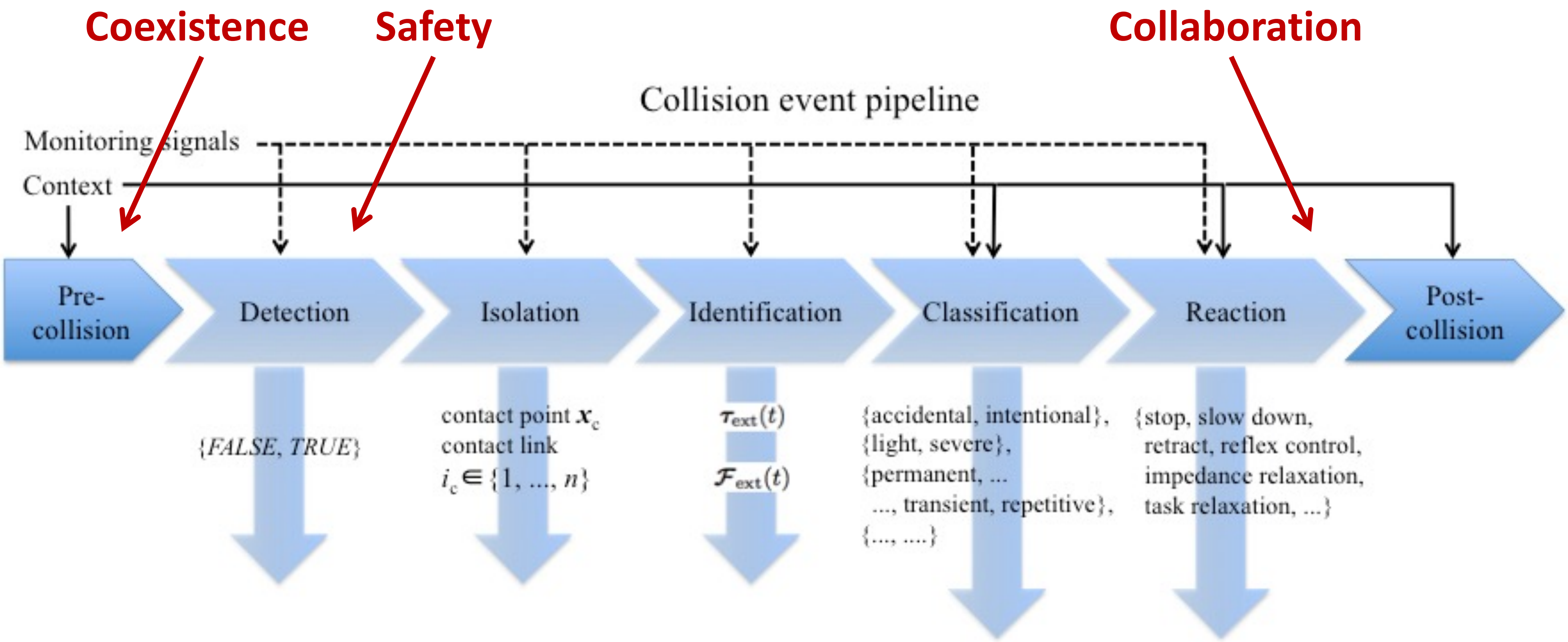
video https://youtu.be/pIIhY8E3HFg



- **collaboration** by manual **contact force** estimation (here, at end-effector only)
- manual guidance **without** using a F/T sensor – more on this later …

Collision event pipeline and its control levels

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

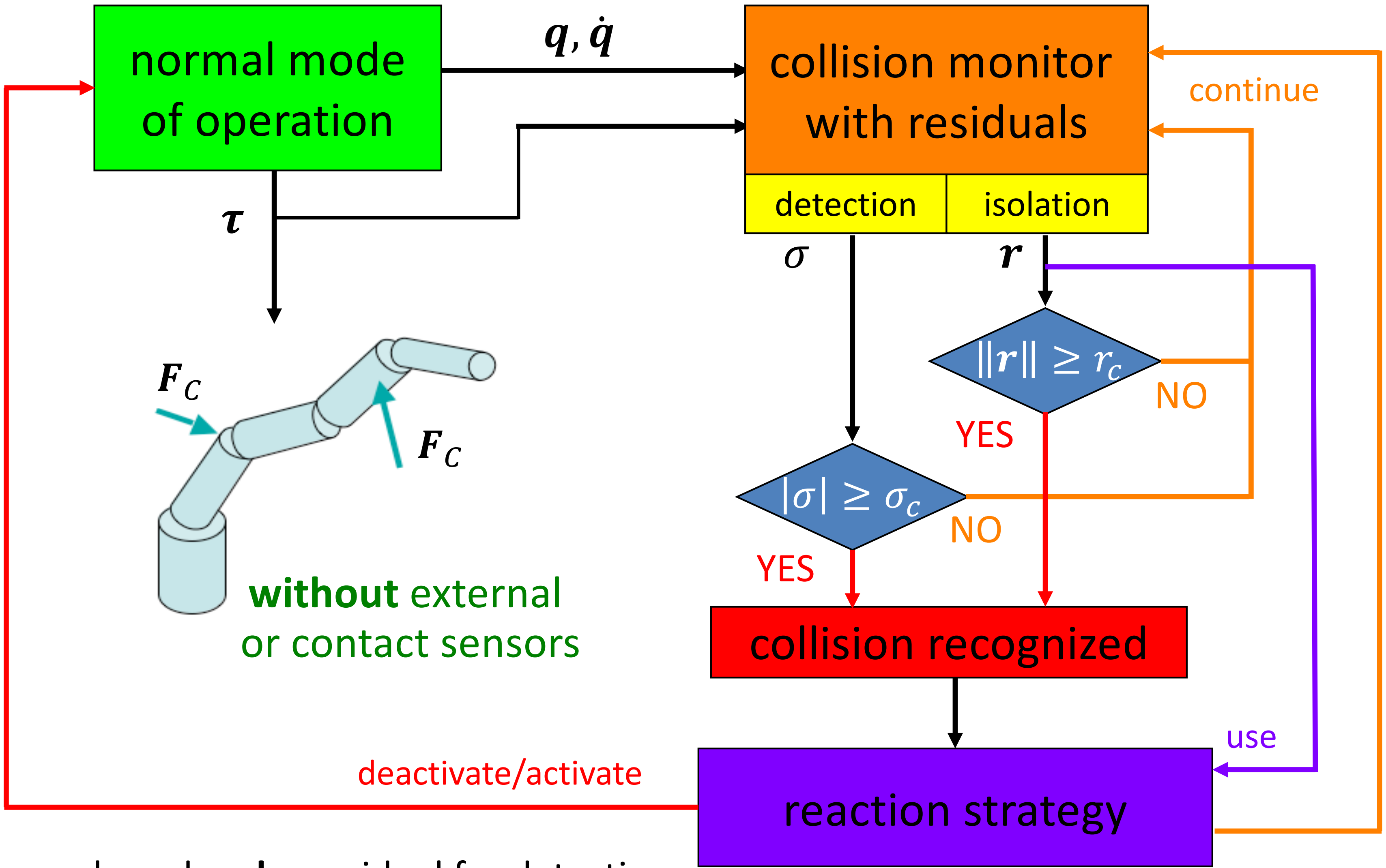


Monitoring signals can be generated from sensors or models (signal- or model-based methods)

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

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

Rigid robots

The physics behind the residuals - 1

dynamic model (with factorization)

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

Coriolis/centrifugal — friction — joint torques due to link collision (anywhere, any time)

$$\boldsymbol{\tau}_C = \boldsymbol{J}_C^T(\boldsymbol{q})\boldsymbol{F}_C$$

total robot energy

$$E = T + U_g = \frac{1}{2}\dot{\boldsymbol{q}}^T\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} + U_g(\boldsymbol{q})$$

kinetic — gravitational

... and its dynamics

$$\dot{E} = \dot{\boldsymbol{q}}^T\left(\boldsymbol{\tau} + \boldsymbol{\tau}_C - \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}})\right)$$

scalar residual

$$\sigma = k_\sigma\left(E - \int_0^t \left(\dot{\boldsymbol{q}}^T\left(\boldsymbol{\tau} - \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}})\right) + \sigma\right) ds\right) \qquad k_\sigma > 0$$

detection property

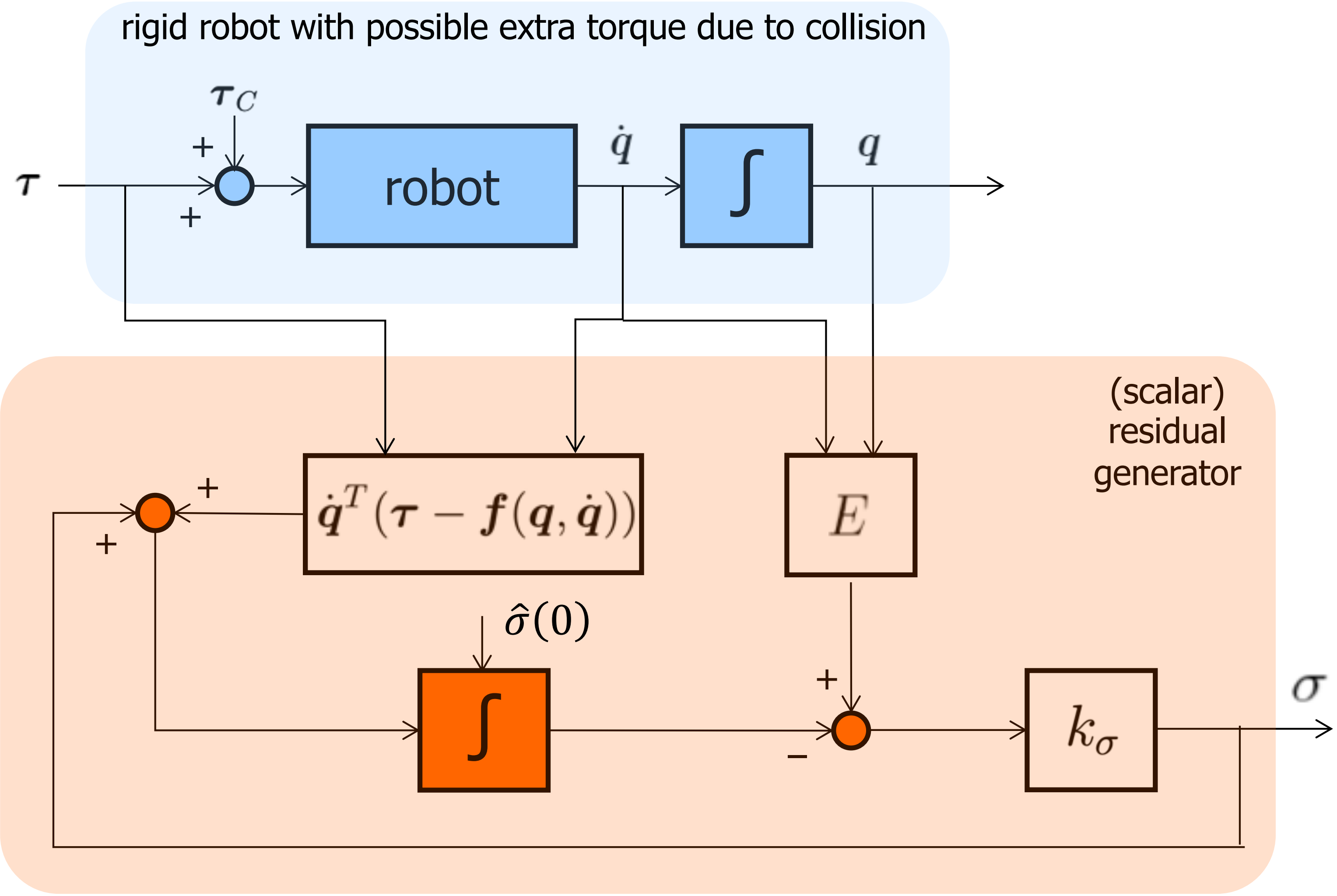
$$\dot{\sigma} = k_\sigma\left(\dot{\boldsymbol{q}}^T\boldsymbol{\tau}_C - \sigma\right)$$

➡ ... but works only when the robot is **in motion** (and **no** isolation)

A. De Luca, A. Albu-Schäffer, S. Haddadin, G. Hirzinger "Collision detection and safe reaction with the DLR-III lightweight manipulator arm," IROS 2006

Energy-based collision detection

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

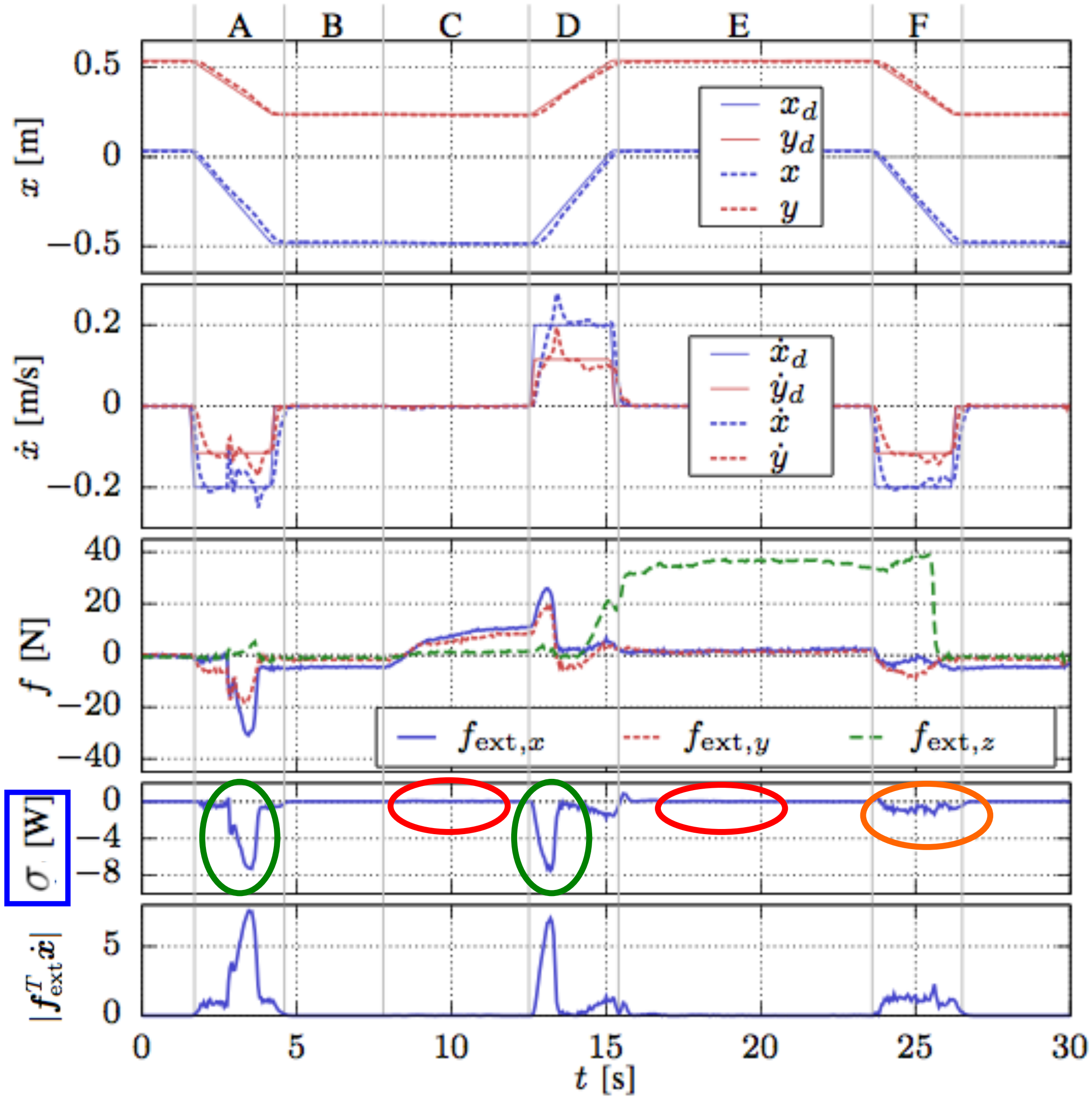


initialization of integrator $\hat{\sigma}(0) = E(0)$ (zero if robot starts at rest)

$$\dot{\sigma} = k_\sigma \left(\dot{\boldsymbol{q}}^T \boldsymbol{\tau}_C - \sigma \right)$$

Collision detection

Experiment with a 6R robot



robot at rest or moving
under Cartesian impedance control
on a straight horizontal line
(with a F/T sensor at wrist for analysis)

6 phases

A: contact force applied is acting against motion direction ⇒ detection

B: no force applied, with robot at rest

C: force increases gradually, but robot is at rest ⇒ no detection

D: robot starts moving again, with force being applied ⇒ detection

E: robot stands still and a strong force is applied in z-direction ⇒ no detection

F: robot moves, with a z-force applied ≈ orthogonal to motion direction ⇒ poor detection

Rigid robots

The physics behind the residuals - 2

dynamic model (with factorization)

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

Coriolis/centrifugal

friction

joint torques due to link collision (anywhere, any time)

$$\boldsymbol{\tau}_C = \boldsymbol{J}_C^T(\boldsymbol{q})\boldsymbol{F}_C$$

skew-symmetric property in momentum dynamics

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

residual vector

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

$$\boldsymbol{K}_r > 0, \text{diagonal}$$

isolation property

$$\dot{\boldsymbol{r}} = \boldsymbol{K}_r\left(\boldsymbol{\tau}_C - \boldsymbol{r}\right)$$

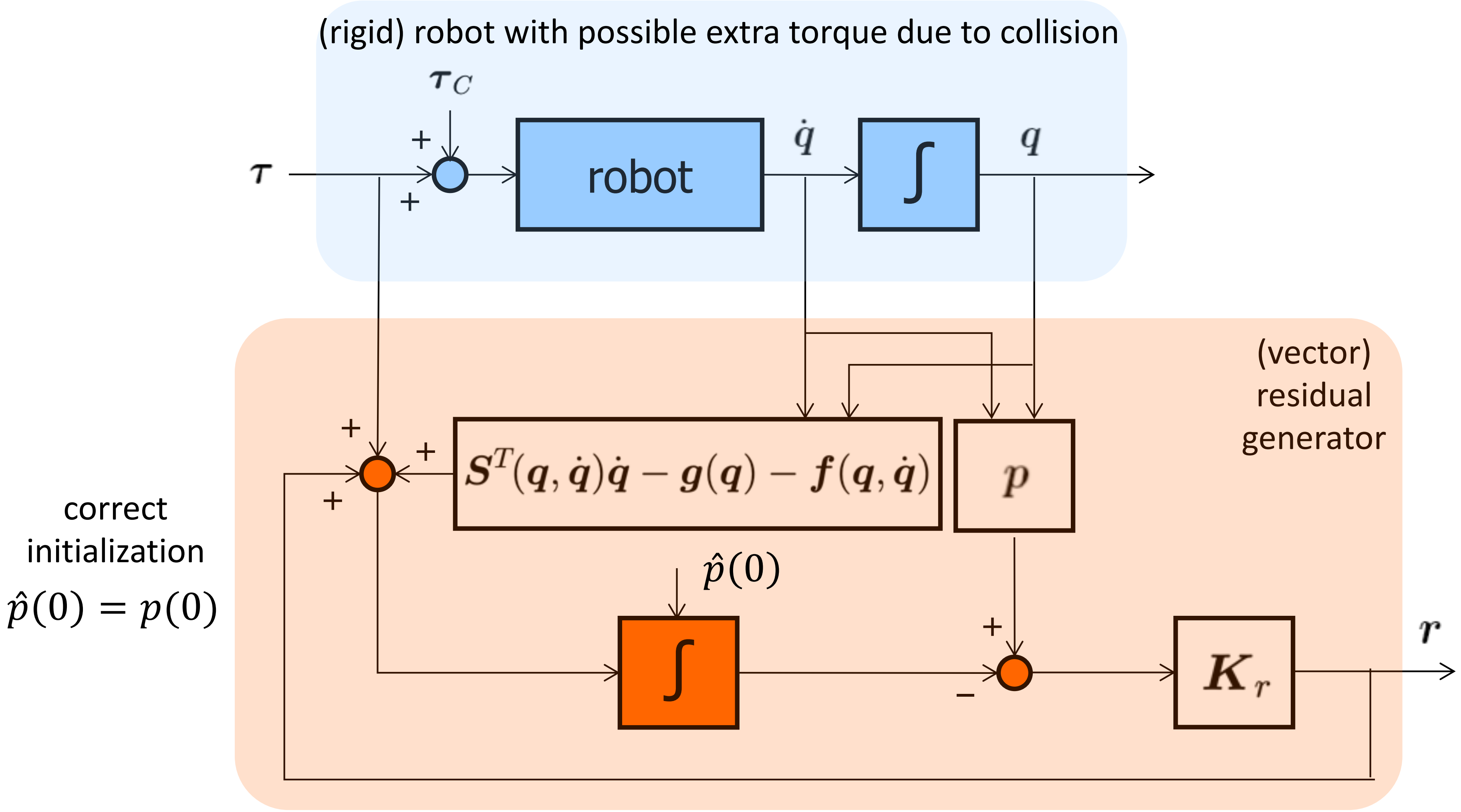
colliding link = largest **index** of residual component exceeding a detection threshold

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

A. De Luca, A. Albu-Schäffer, S. Haddadin, G. Hirzinger "Collision detection and safe reaction with the DLR-III lightweight manipulator arm," IROS 2006

Momentum-based collision detection and isolation

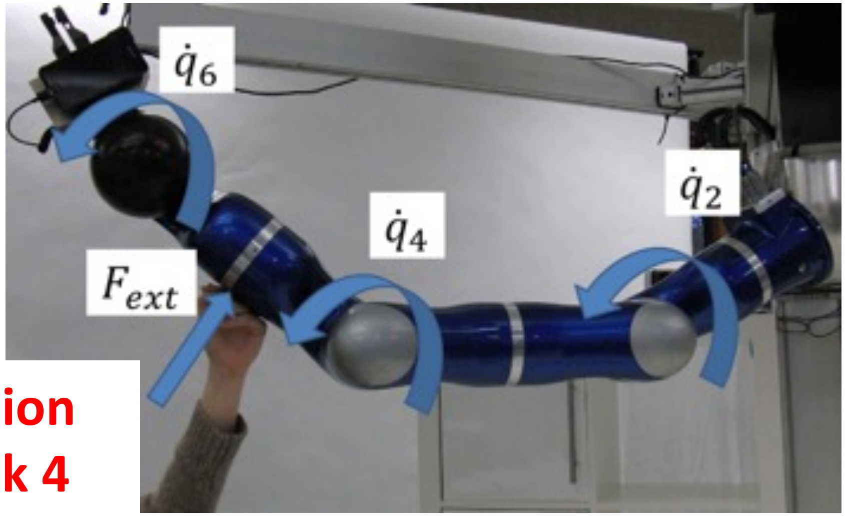
Block diagram for the generator of a vector residual signal (ICRA 2005, IROS 2006)



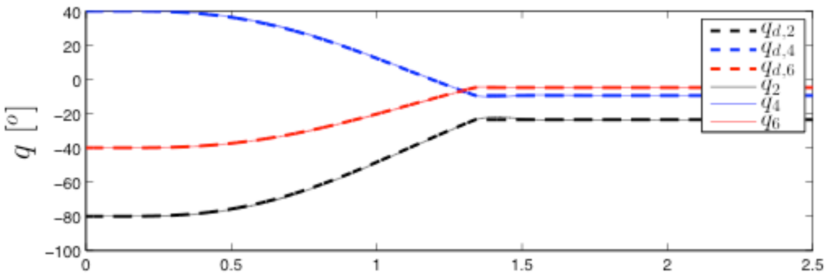
$$\dot{r} = K_r\,(\tau_C - r)$$

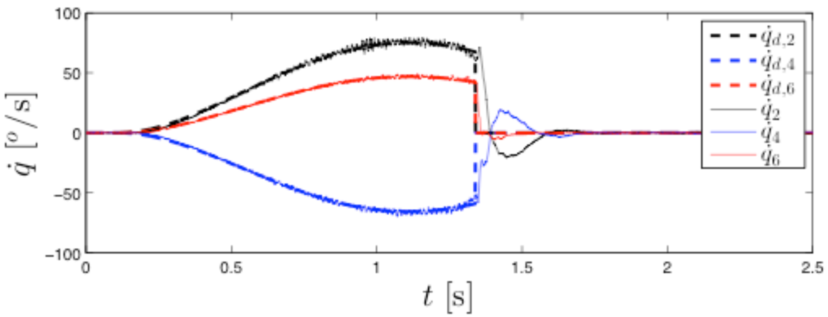
Isolation property of link collisions

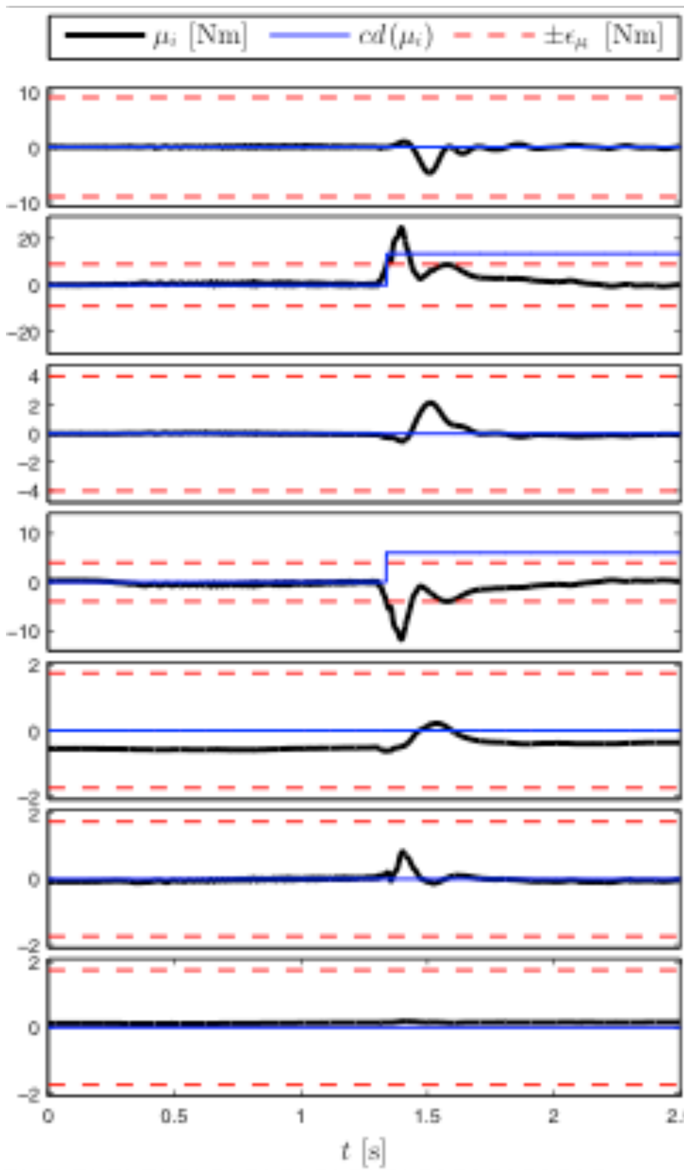
Experiment with a position-controlled DLR LWR-III 7R robot while three links are in motion



collision at link 4







thresholds

cd_1 = off

cd_2 = ON

cd_3 = off

cd_4 = ON

cd_5 = off

cd_6 = off

cd_7 = off

thresholds

Collision detection and reaction

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

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

3 videos

admittance mode	reflex torque	reflex torque
first impact at 60°/s		first impact at 90°/s
$\dot{q}_r = K_Q r$	$\tau = K_R r$	

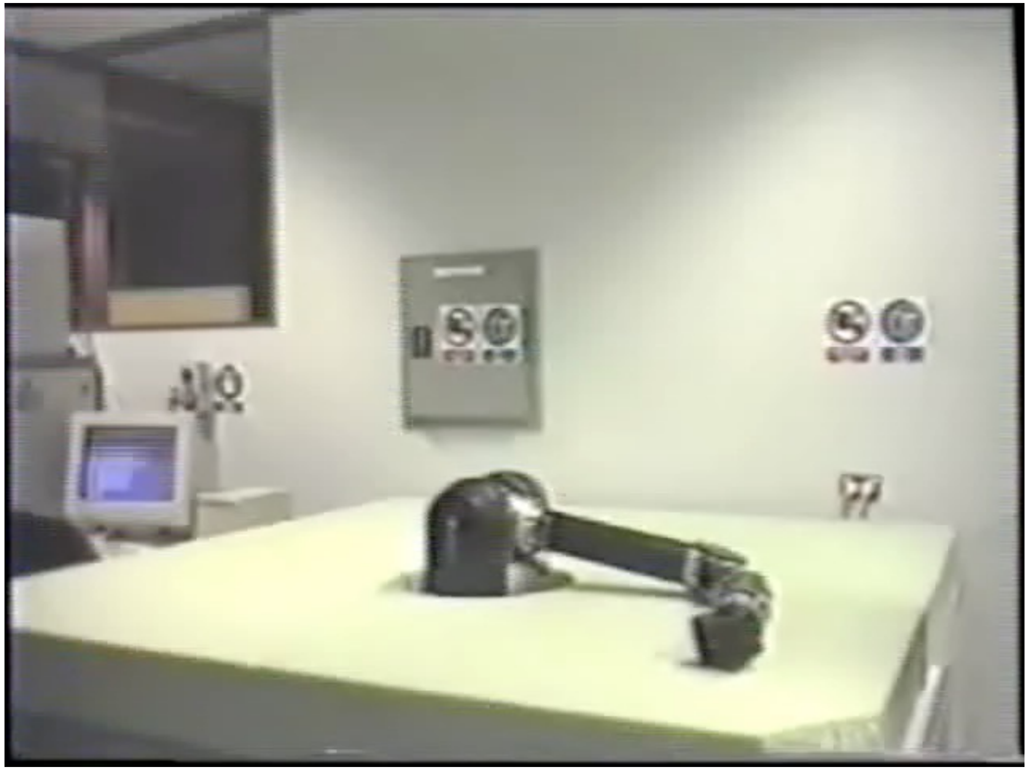
Zero gravity operation

Correct or under- and overcompensation

video

http://handbookofrobotics.org/view-chapter/69/videodetails/611

video



WAM Barrett
(Heinzmann, Zelinsky, IJRR 2003)

$$\tau = \tau' + g(q)$$

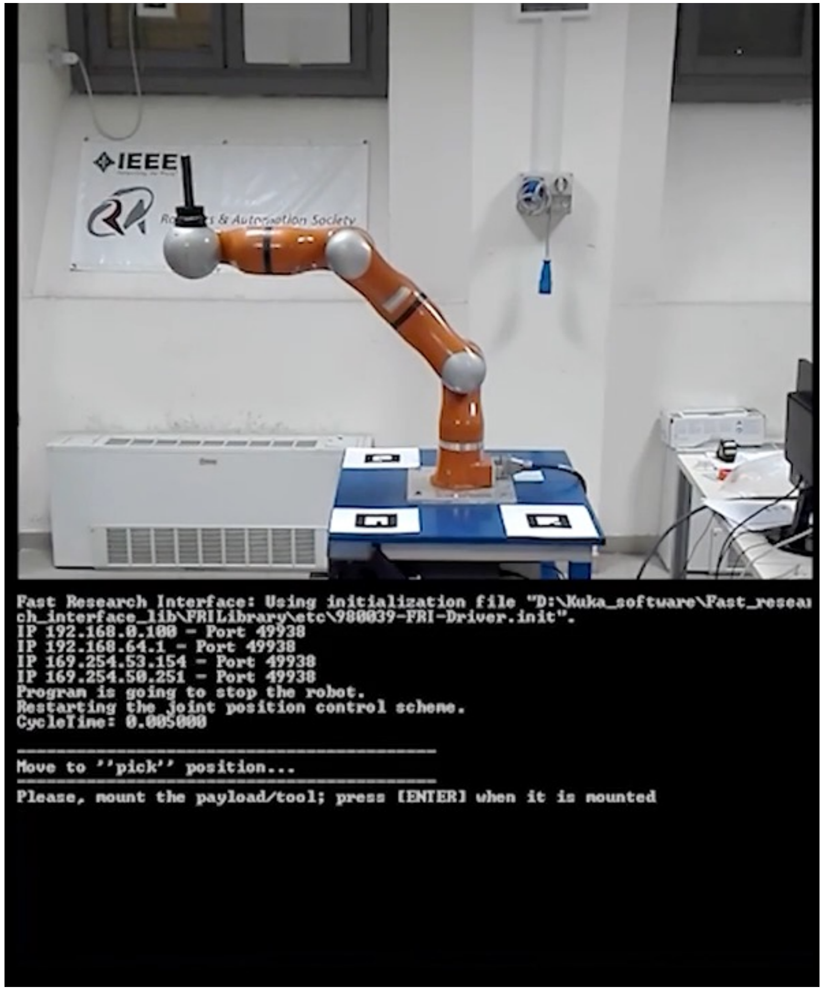
KUKA LWR4 @DLR
(around 2006)

here, only as result of human pushes …

Sensitivity to payload changes/uncertainty

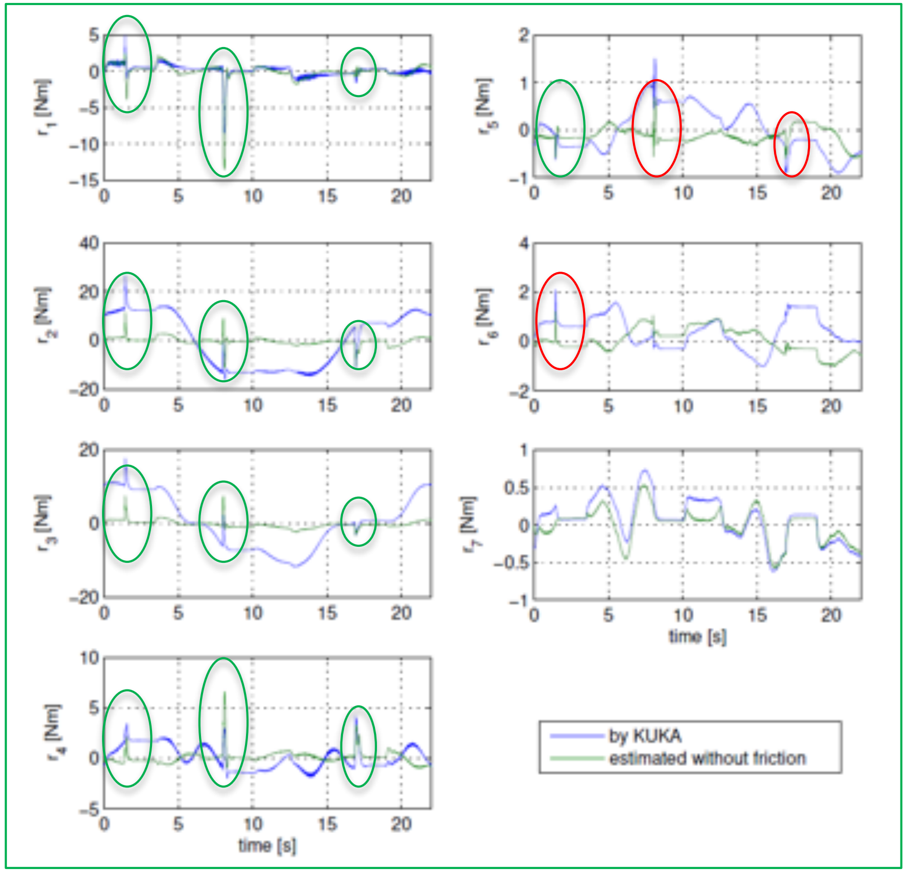
Collision detection and isolation after few moves for identification (IROS 2017)

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



video https://youtu.be/fNP6smdp7aE

residuals with online estimated payload after 10 positioning

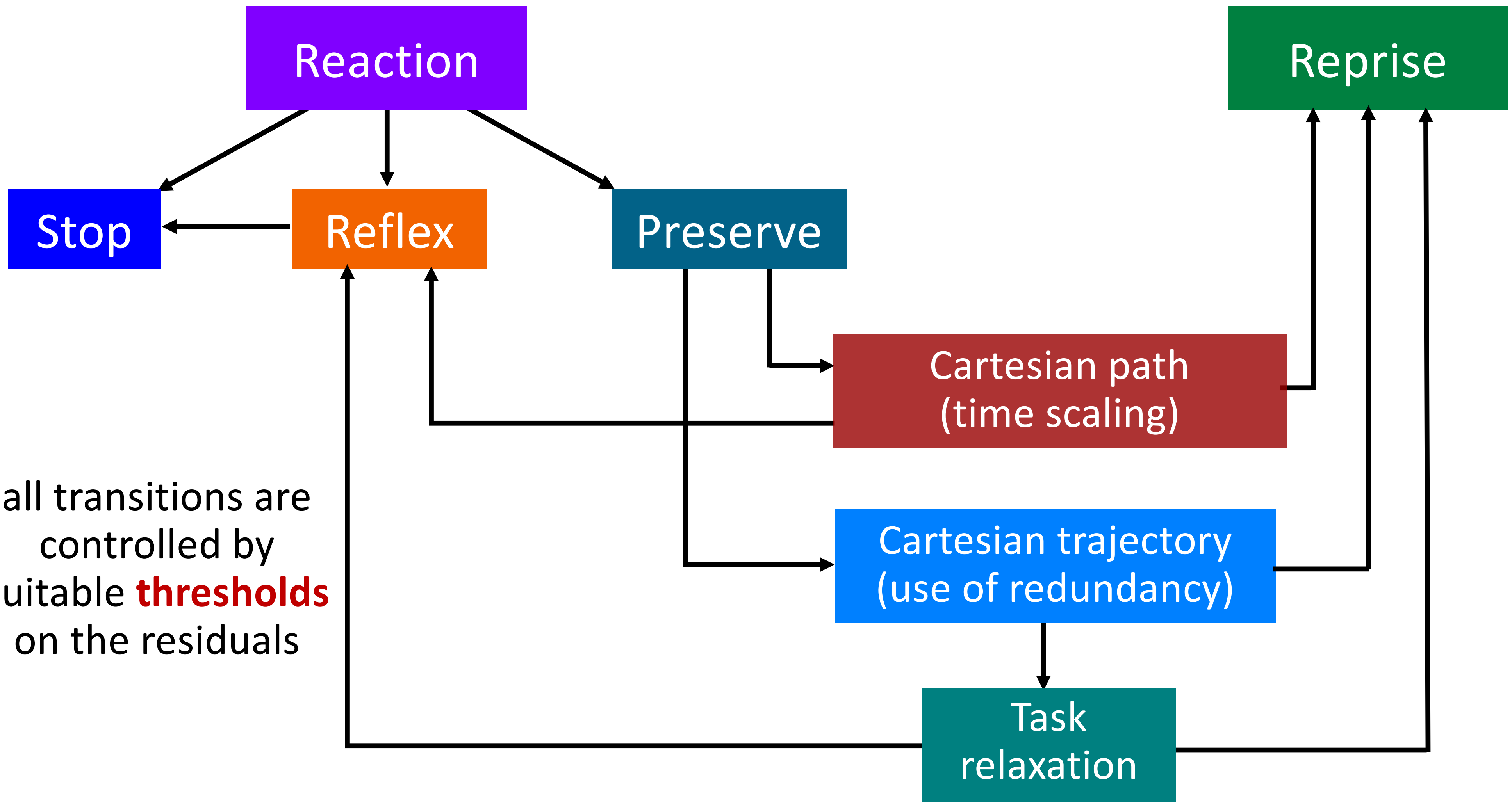


three collisions (link 6 ⇢ 5 ⇢ 5) **detected** & **isolated** by the residuals when exceeding their thresholds (6 Nm for first 4 joints, 2 Nm for last 3)

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

Some examples (IROS 2008)

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

video

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

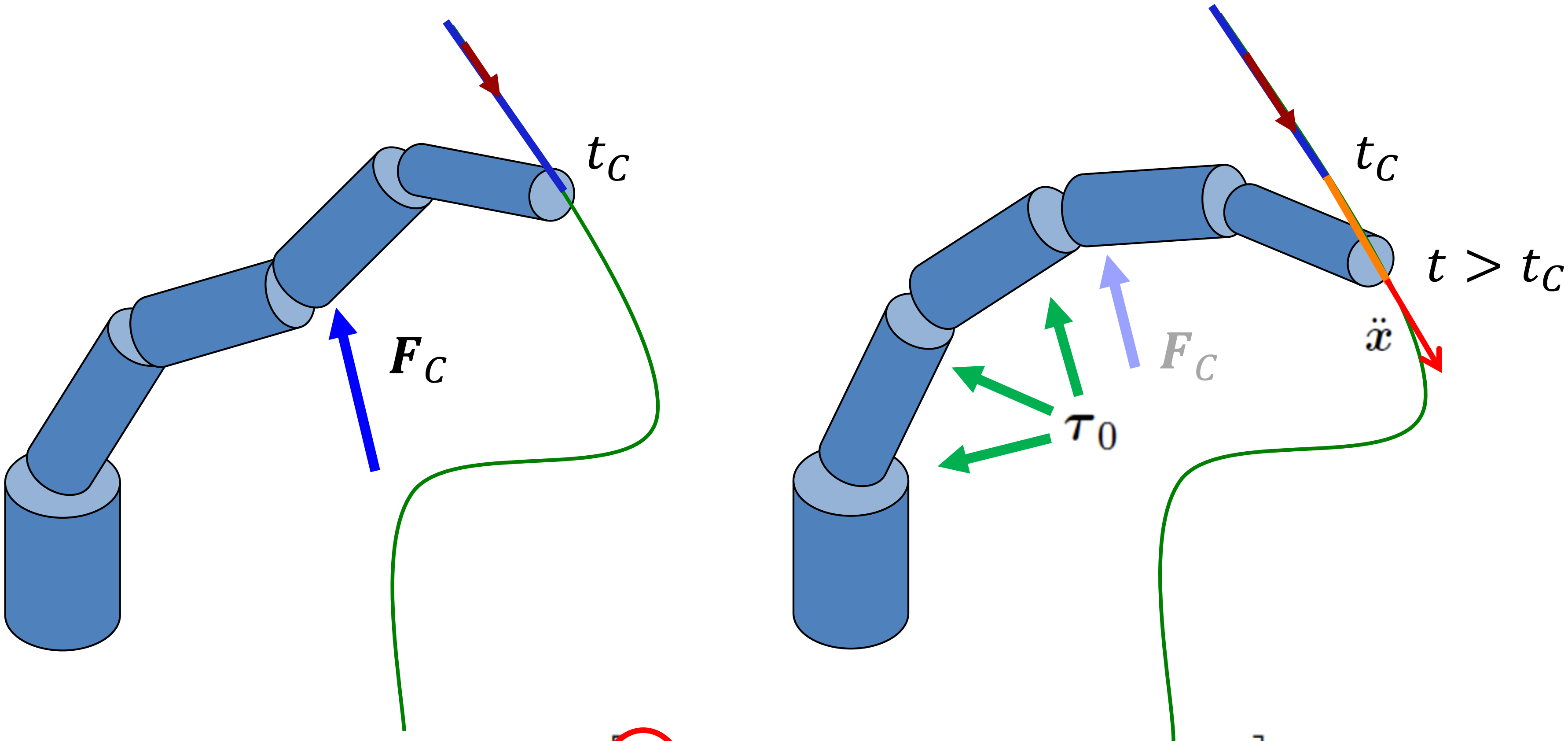
video

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

Use of kinematic redundancy in pHRI

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

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



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

Use of kinematic redundancy

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

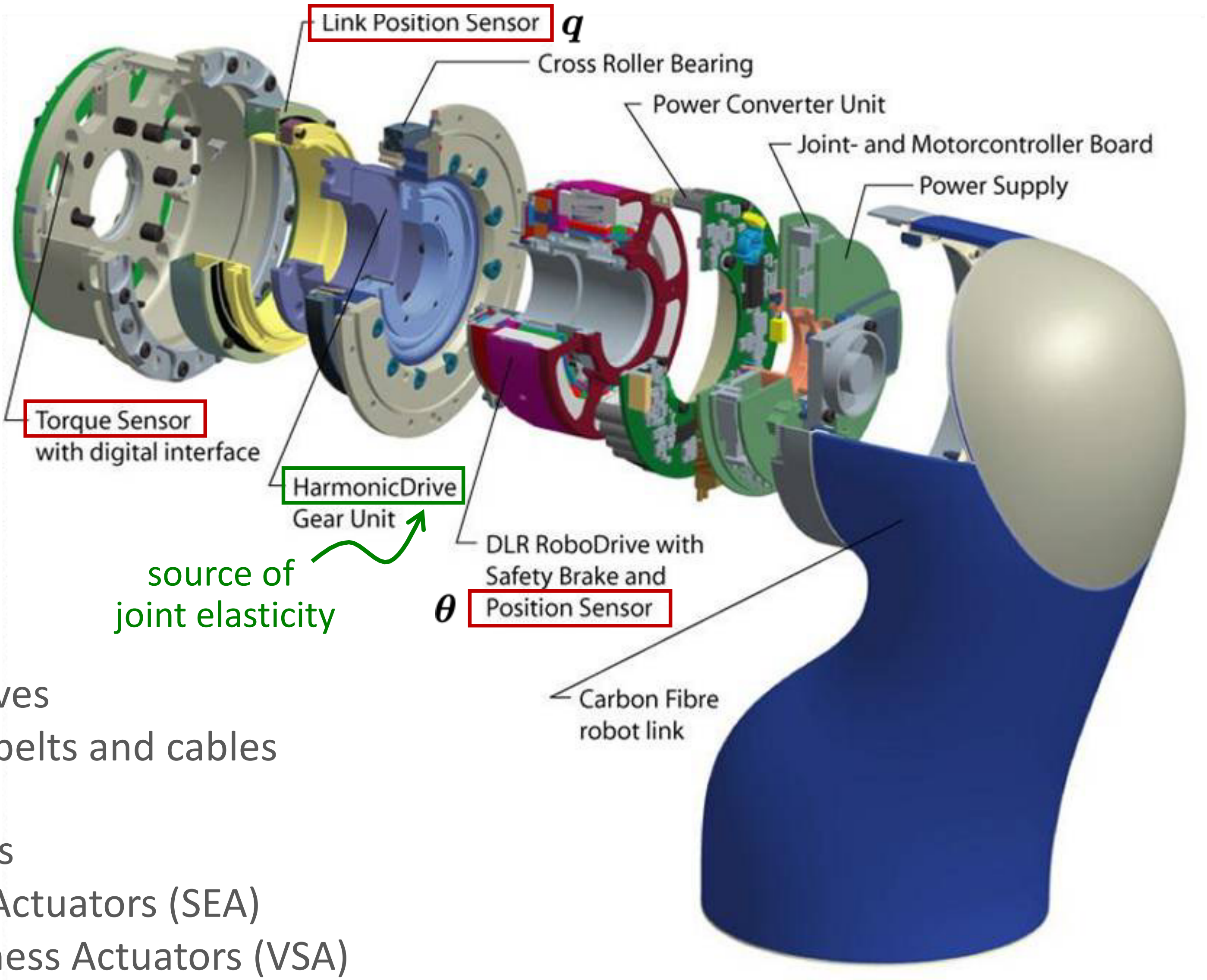
video https://youtu.be/q4PZKE-kgc0

idle ⇔ relax ⇔ abort

Sources of joint elasticity

Harmonic Drives in the DLR-KUKA LWR series of lightweight collaborative robots

$$\boldsymbol{\tau}_J = \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q})$$



- Harmonic Drives
- transmission belts and cables
- long shafts
- cycloidal gears
- Serial Elastic Actuators (SEA)
- Variable Stiffness Actuators (VSA)

Robots with elastic joints

Dynamic model and physical properties

dynamic model (with **Spong** simplifying assumption)

$$\begin{cases} \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau}_J + \boldsymbol{\tau}_C & \text{link equation} \\ \boldsymbol{M}_m\ddot{\boldsymbol{\theta}} + \boldsymbol{f}_m(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{\tau}_J = \boldsymbol{\tau} & \text{motor equation} \end{cases}$$

motor friction (dominant)

link equation

motor equation

$$\boldsymbol{\tau}_J = \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q})$$

joint elastic torque

generalized momentum

$$\boldsymbol{p} = \begin{pmatrix} \boldsymbol{p}_q \\ \boldsymbol{p}_\theta \end{pmatrix} = \begin{pmatrix} \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} \\ \boldsymbol{M}_m\dot{\boldsymbol{\theta}} \end{pmatrix}$$

$$\boldsymbol{p}_q = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} \; (= \boldsymbol{p} \text{ of the rigid case})$$

$$\dot{\boldsymbol{p}}_\theta = \boldsymbol{\tau} - \boldsymbol{\tau}_J - \boldsymbol{f}_m(\boldsymbol{q},\dot{\boldsymbol{q}})$$

total robot energy

elastic energy

$$\begin{aligned} E_{EJ} &= T_q + T_m + U_g + U_e \\ &= \frac{1}{2}\dot{\boldsymbol{q}}^T\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}} + \frac{1}{2}\dot{\boldsymbol{\theta}}^T\boldsymbol{M}_m\dot{\boldsymbol{\theta}} + U_g(\boldsymbol{q}) + \frac{1}{2}(\boldsymbol{\theta} - \boldsymbol{q})^T\boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q}) \end{aligned}$$

$$E_q = T_q + U_g \; (= E \text{ of the rigid case})$$

$$\dot{E}_{EJ} = \dot{\boldsymbol{q}}^T\boldsymbol{\tau}_C + \dot{\boldsymbol{\theta}}^T(\boldsymbol{\tau} - \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}}))$$

A. De Luca, W. Book "Robot with flexible elements" Chapter 11 in B. Siciliano, O. Khatib (Eds.) Springer Handbook of Robotics, 2016

Robots with elastic joints

Link collisions – alternatives for vector and scalar residuals

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

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

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

detection and isolation property

$$\dot{\boldsymbol{r}}_{EJ} = \boldsymbol{K}_r \left(\boldsymbol{\tau}_C - \boldsymbol{r}_{EJ} \right)$$

no use of joint stiffness (good also for **VSA**!)

$$\sigma_{EJ}(t) = k_\sigma \left(E_q - \int_0^t \left(\dot{\boldsymbol{q}}^T \boldsymbol{\tau}_J + \sigma_{EJ} \right) ds \right)$$

$$\sigma_{EJ}(t) = k_\sigma \left(E_q - \int_0^t \left(\dot{\boldsymbol{q}}^T \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q}) + \sigma_{EJ} \right) ds \right)$$

$$\sigma_{EJ}(t) = k_\sigma \left(E_{EJ} - \int_0^t \left(\dot{\boldsymbol{\theta}}^T \left(\boldsymbol{\tau} - \boldsymbol{f}_m(\boldsymbol{q}, \dot{\boldsymbol{q}}) \right) + \sigma_{EJ} \right) ds \right)$$

no need of joint torque sensors (best for **SEA**!)

$$\dot{\sigma}_{EJ} = k_\sigma \left(\dot{\boldsymbol{q}}^T \boldsymbol{\tau}_C - \sigma_{EJ} \right)$$

detection only (with robot in motion)

Link collisions

Experiments on a Neura LARA 5 cobot (rigid model, no joint torque sensors)

video

- **scalar** and **vector** residuals σ and $\boldsymbol{r}$ can also be **used together** to improve thresholding performance in avoiding false positive or false negative collision events

D. Zurlo, T. Heitmann, M. Morlock, A. De Luca "Collision detection and contact point estimation using virtual joint torque sensing applied to a cobot," ICRA 2023

Reduced-order velocity observer for rigid robots

Avoiding numerical differentiation of encoder positions

- to be used in output feedback control laws and for collision detection/isolation
- nice to have the same first-order structure of momentum-based residual
- should work in closed-loop or open-loop mode (with possibly unbounded velocity)

$$\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{z}} = \boldsymbol{\tau} - \boldsymbol{S}(\boldsymbol{q},\hat{\dot{\boldsymbol{q}}})\,\hat{\dot{\boldsymbol{q}}} - \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{f}(\boldsymbol{q},\hat{\dot{\boldsymbol{q}}}) - k_0\,\boldsymbol{M}(\boldsymbol{q})\hat{\dot{\boldsymbol{q}}}$$

$$\hat{\dot{\boldsymbol{q}}} = \boldsymbol{z} + k_0\,\boldsymbol{q}$$

Theorem 1. Assume that $\|\dot{q}\| \leq v_{max}$ is known. Then, for any fixed $\eta > 0$, by choosing

$$k_0 \geq (c_0 v_{max} + \eta)/\lambda_{min}(\boldsymbol{M}(\boldsymbol{q}))$$

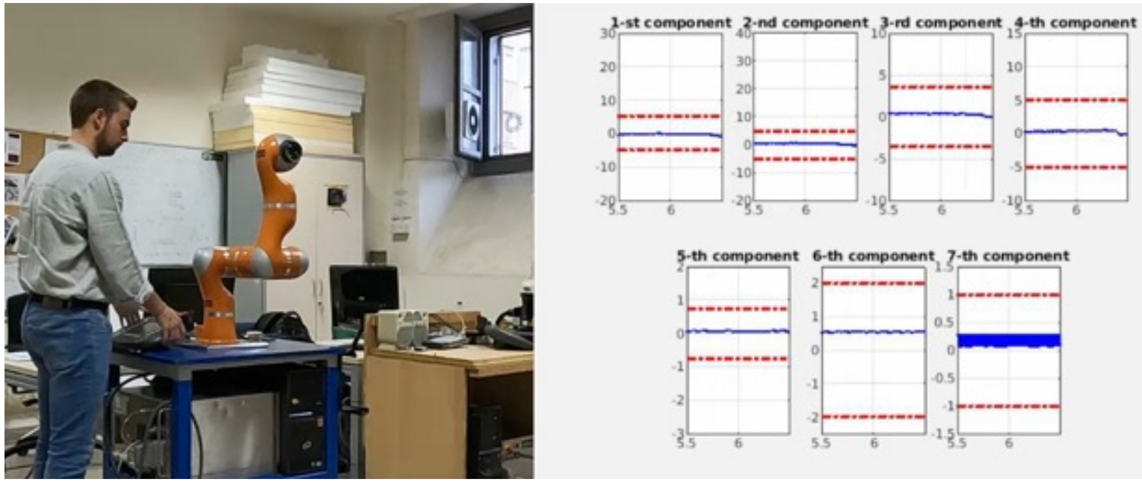
we obtain **local exponential stability** of the observation error $\boldsymbol{\varepsilon} = \dot{\boldsymbol{q}} - \widehat{\dot{\boldsymbol{q}}}$ with a region of attraction $\mathcal{E}(\eta)$.

- **faster** convergence than with full-order observer (e.g., Nicosia-Tomei IEEE T-AC 1990)
- **robust** with respect to noisy measurements and model uncertainties

A. Cristofaro, A. De Luca "Reduced-order observer design for robot manipulators," IEEE Control Systems Letters, vol. 7, pp. 520-525, 2023

Use of position-based residual for collisions

Experiments on a KUKA LWR4 with momentum-based residual using the velocity observer



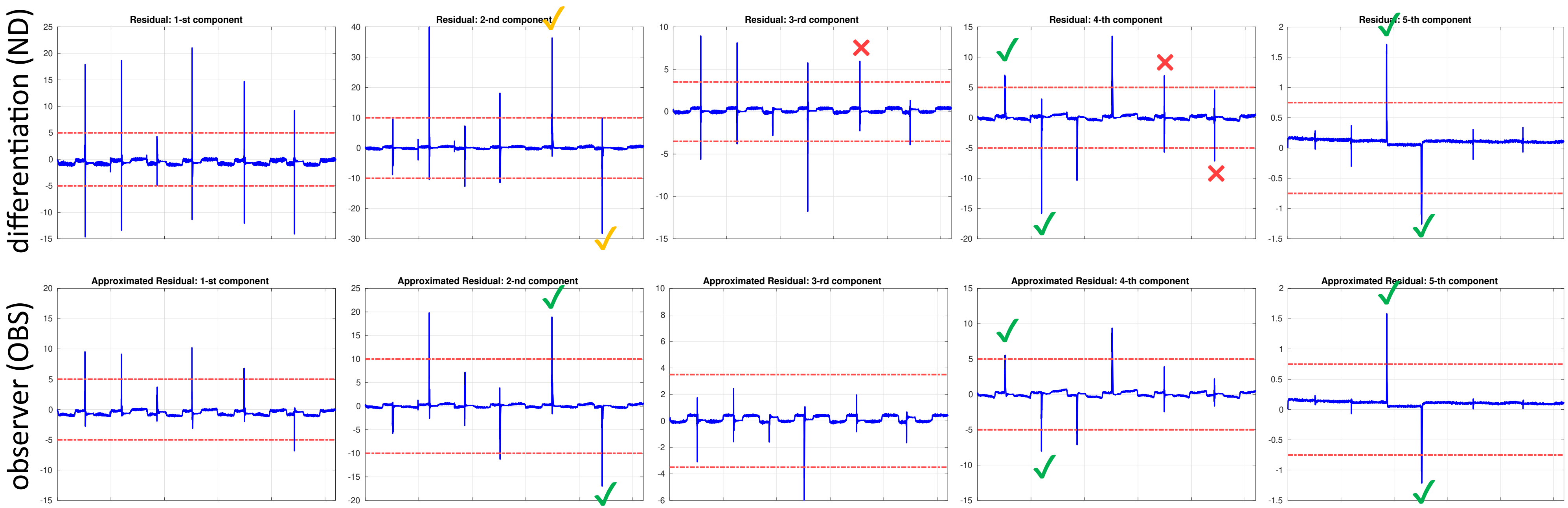
- numerical differentiation vs. observer
- 6 link collisions in sequence (over 30 s):

L4 (twice, ±) ⇒ L5 (twice, ±) ⇒ L2 (twice, ±)

- both methods detect collisions correctly
- ND has two false isolations (#5 and #6)
- OBS isolates the colliding link correctly

video

only first 5 residuals are shown (out of 7)

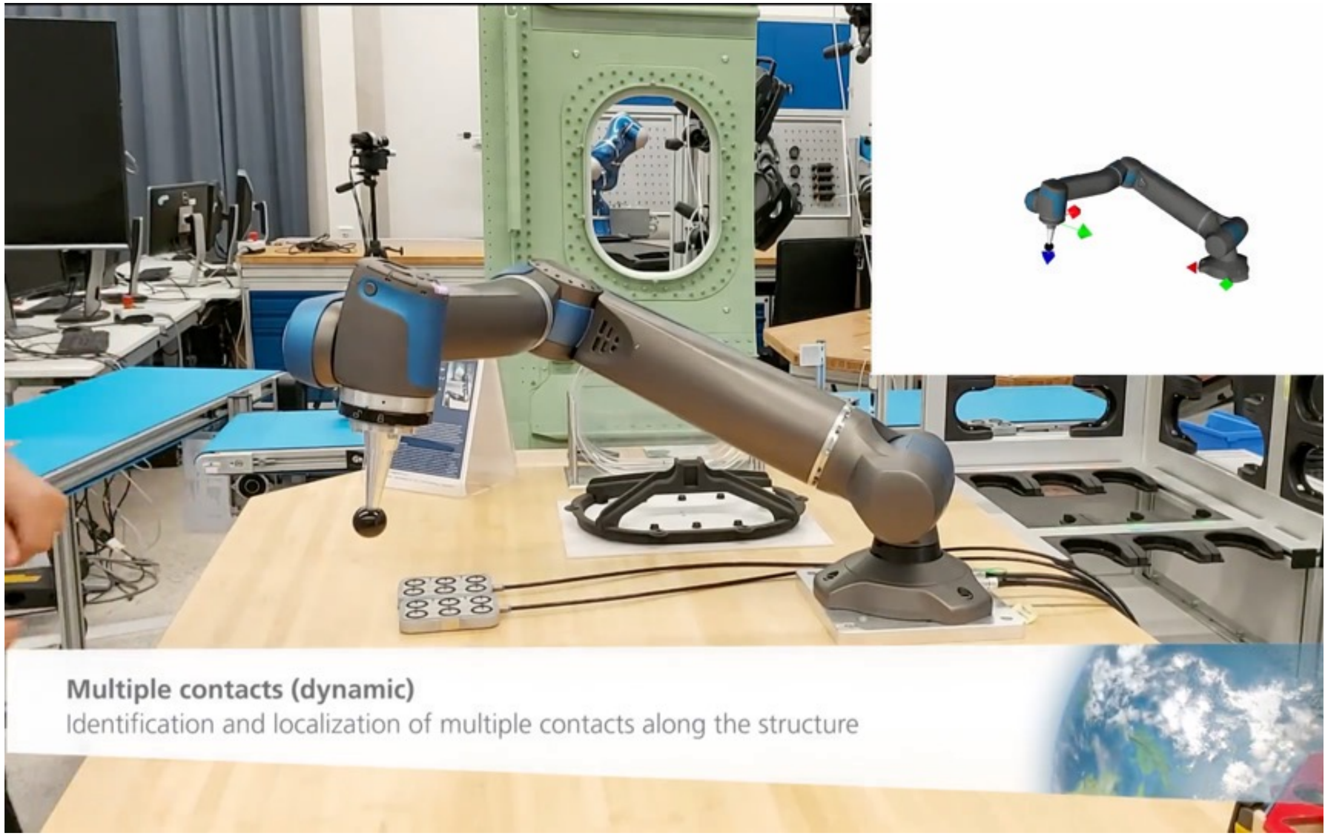


Enhanced collision detection & identification

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

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

video



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

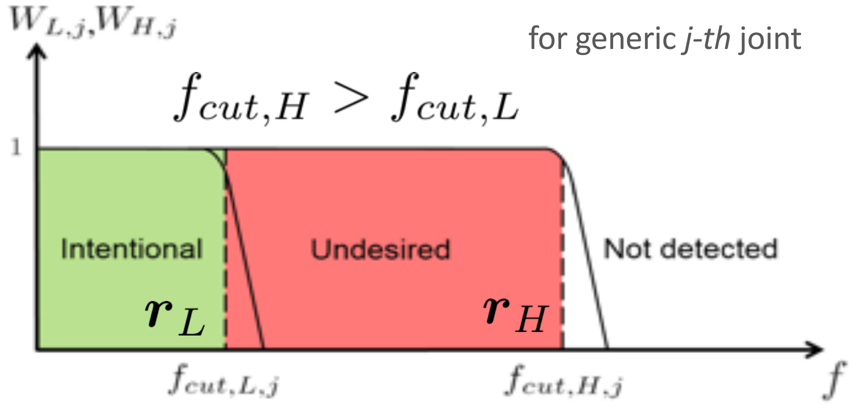
Collision or collaboration?

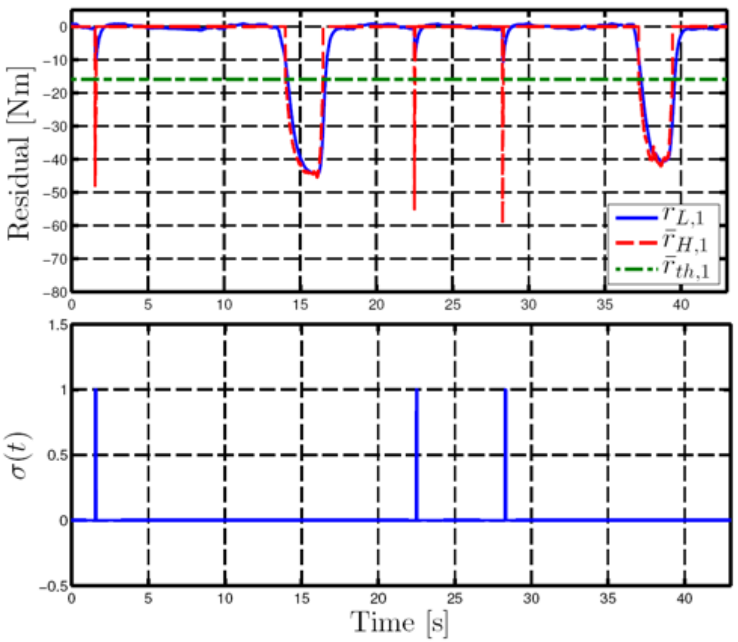
Distinguishing hard/accidental collisions and soft/intentional contacts

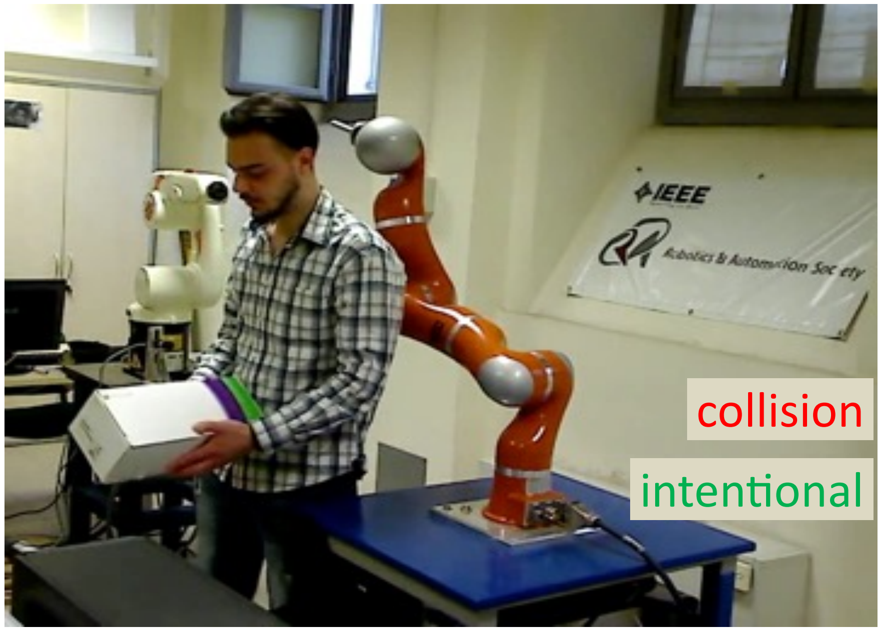
- using suitable low and high bandwidths for the residuals (first-order stable filters)

$$\dot{\boldsymbol{r}} = \boldsymbol{K}_r \left(\boldsymbol{\tau}_C - \boldsymbol{r}\right)$$

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





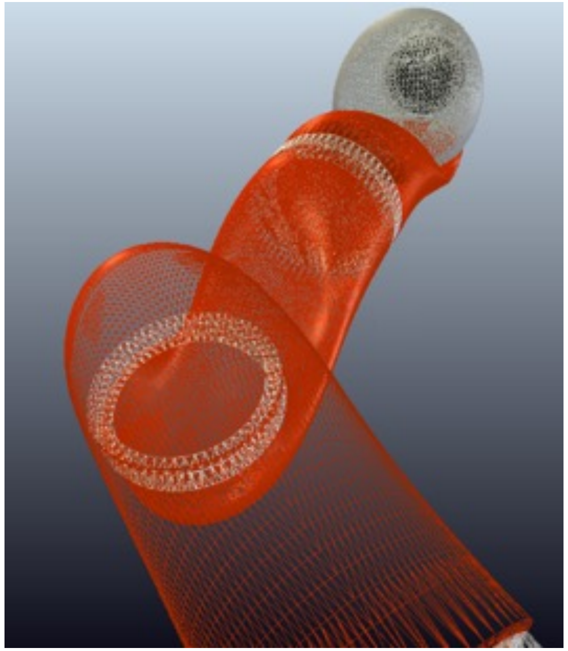


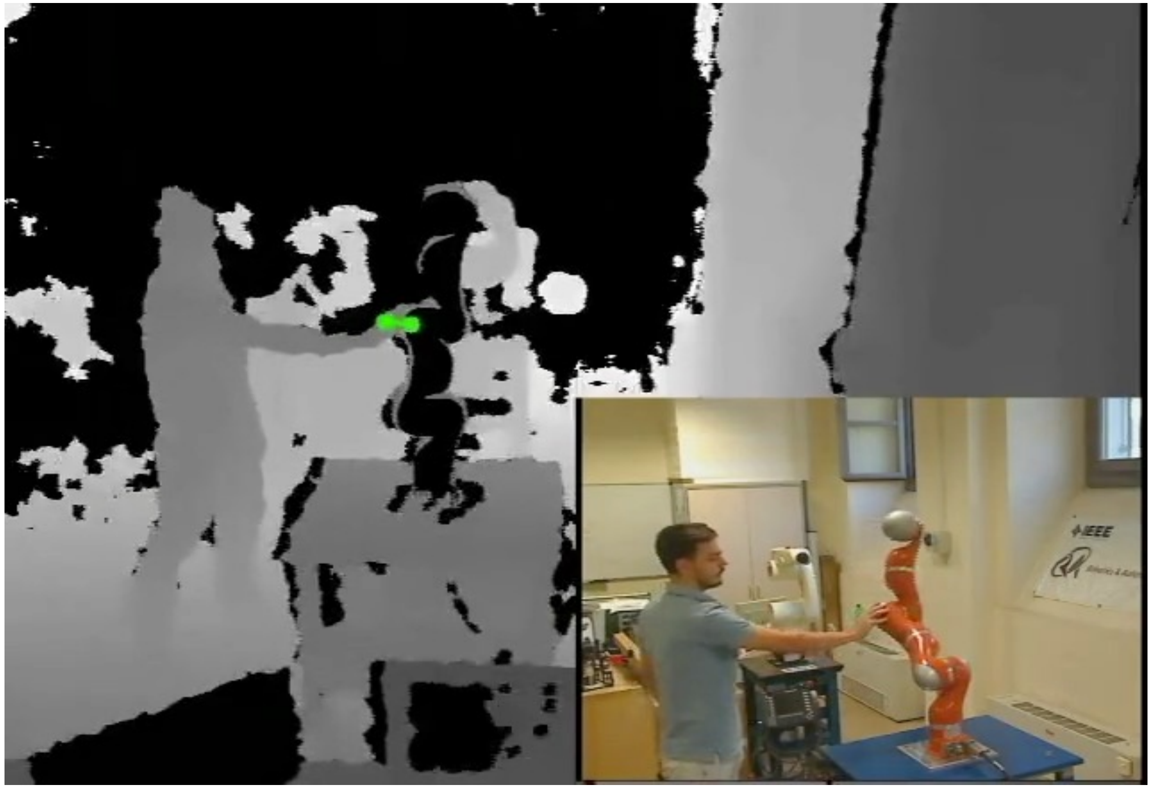
video

Distance and contact estimation

Combining Kinect, CAD model, distance computation, and residual to localize contact

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





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 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

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

$$\Rightarrow \begin{pmatrix} \widehat{\boldsymbol{F}}_c \\ \widehat{\boldsymbol{M}}_c \end{pmatrix} = \left(\boldsymbol{J}_c^T(\boldsymbol{q})\right)^{\#} \boldsymbol{r}$$

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

Validation of virtual force sensor

Experiments in static conditions with the KUKA LWR 4

- evaluation of estimated contact force

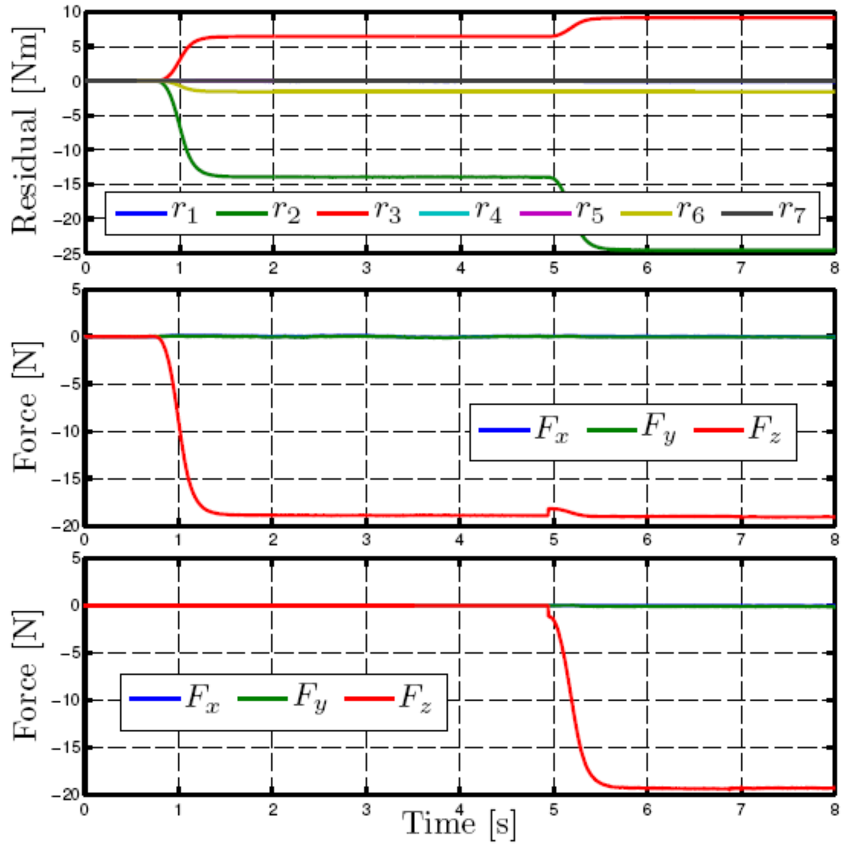
$$\widehat{\boldsymbol{F}}_c = \left(\boldsymbol{J}_c^T(\boldsymbol{q})\right)^{\#} \boldsymbol{r}$$

  - 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 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

Control based on contact force estimation

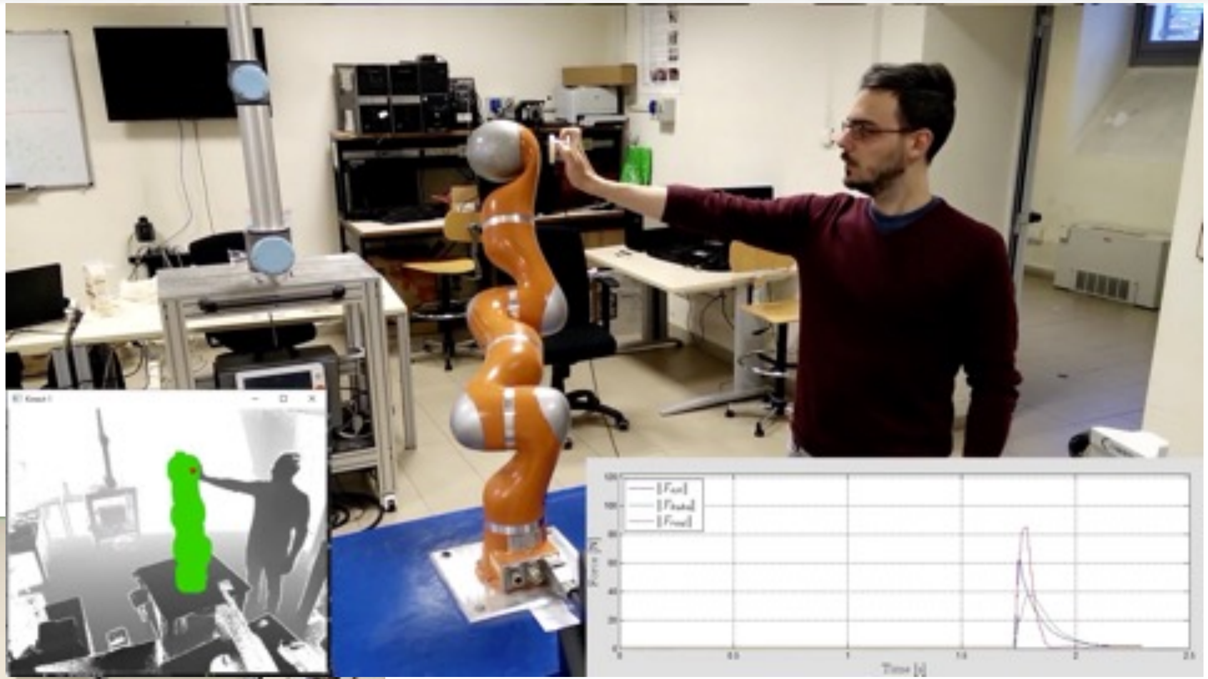
Used within an admittance control scheme (IROS 2014)

video http://youtu.be/Yc5FoRGJsrc

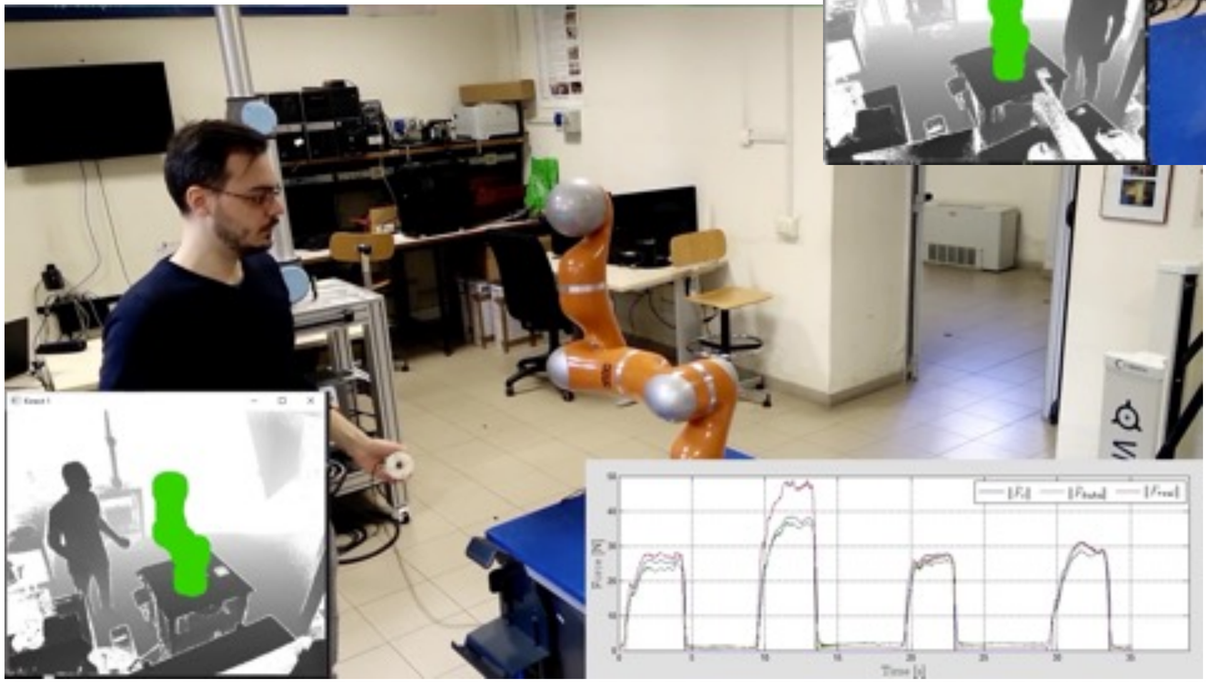
Further validation of virtual force sensor

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)



video



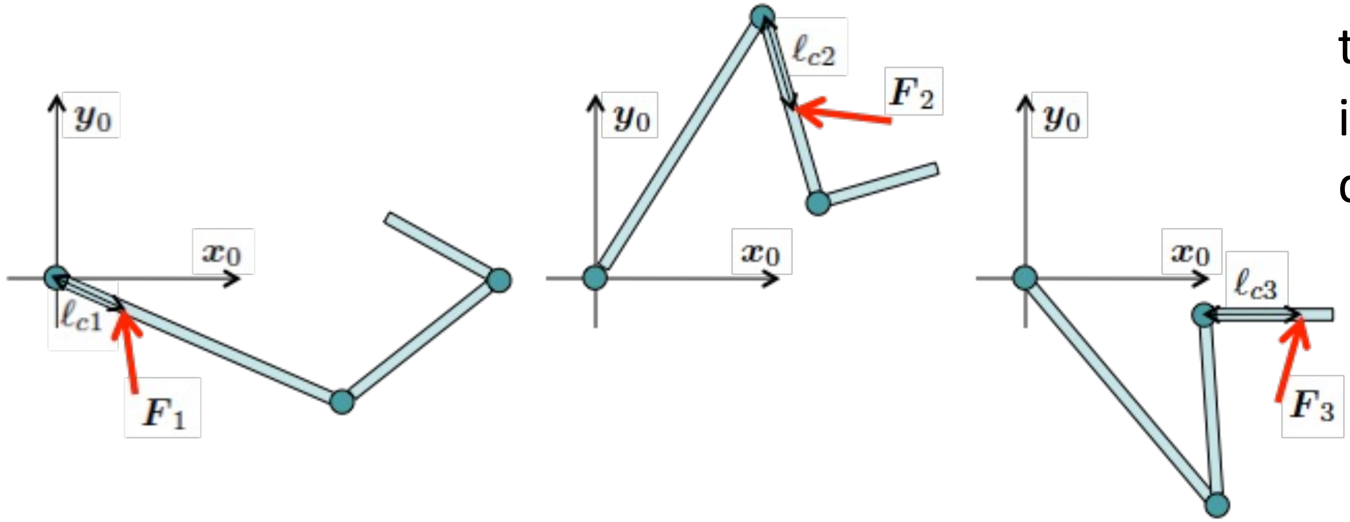
video

Emanuele Magrini PhD thesis

A closer analysis of contact force estimation

Which force components are being estimated? Do we really need external sensing?

- a simple 3R planar case, with contact on different links



the residual $\boldsymbol{r}$ is a vector of dimension 3

rank { J_{c1} } = 1

rank { J_{c2} } = 2

rank { J_{c3} } = 2

$\hat{F}_i$

only normal force to link, if contact point is known (**1** informative residual signal)

full force on link, if contact point is known (**2** informative residuals)

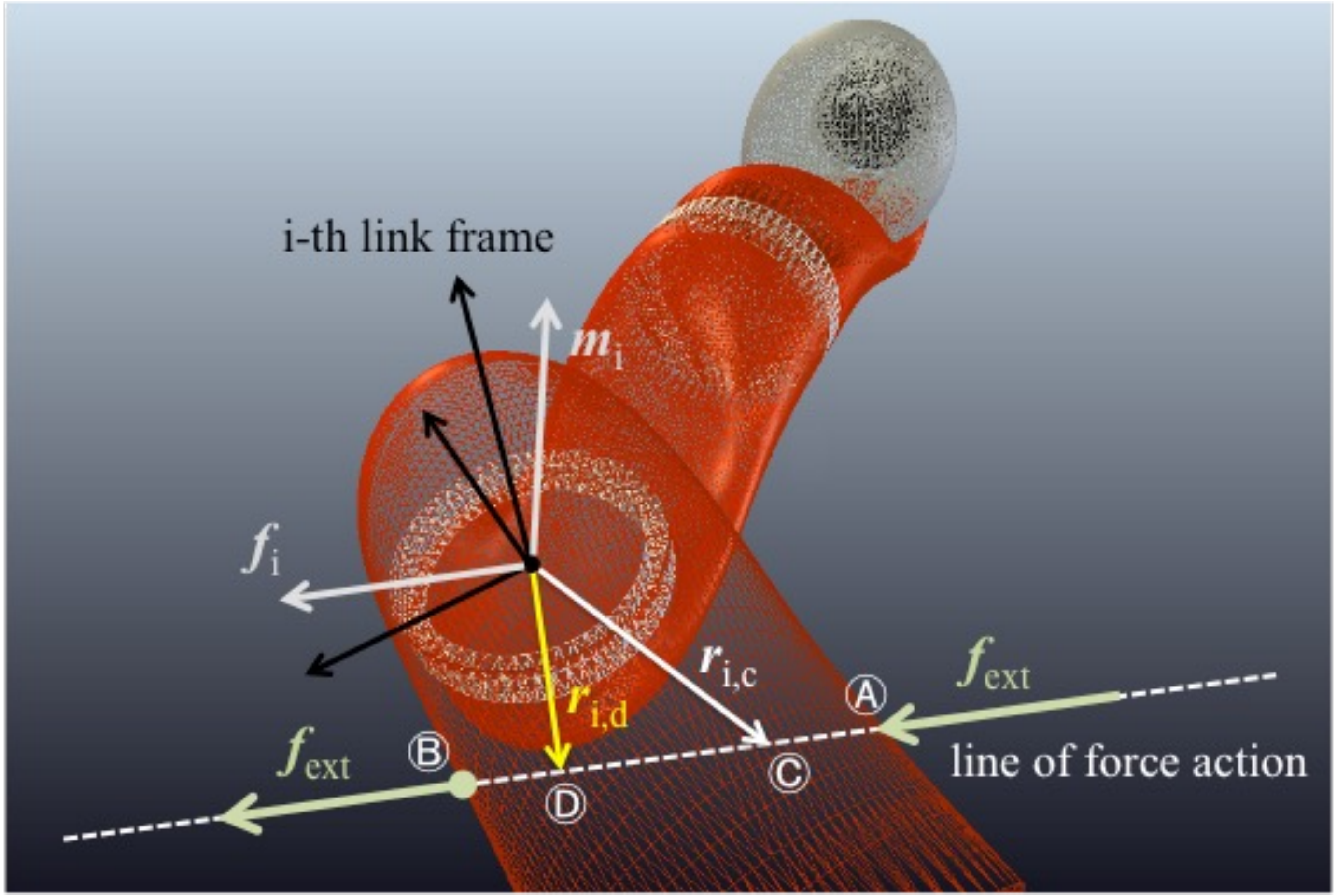
full force on link, **even without** knowing contact (**3** informative residuals)

- forces $F_k \in \mathcal{N}(J_k^T(q))$ will never be recovered (even with known contact)

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** ...



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-velocity** 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

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

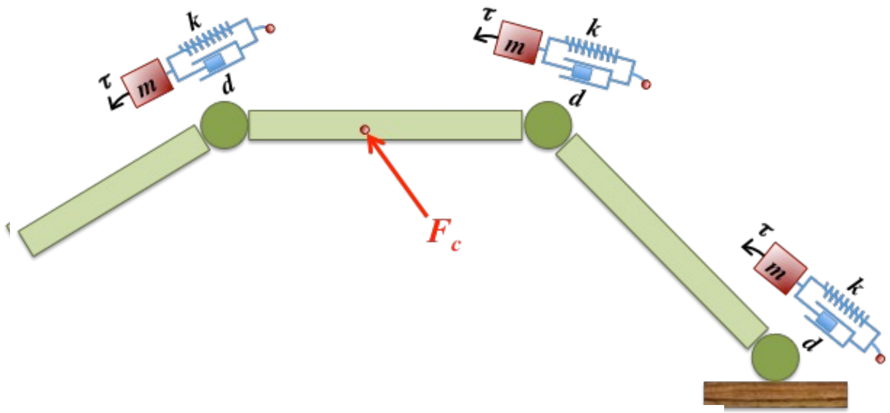
$$\boldsymbol{F}_a = \widehat{\boldsymbol{F}}_c + \boldsymbol{K}_p(\boldsymbol{p}_d - \boldsymbol{p}_c), \qquad \boldsymbol{K}_p = k_p \boldsymbol{I} > 0$$

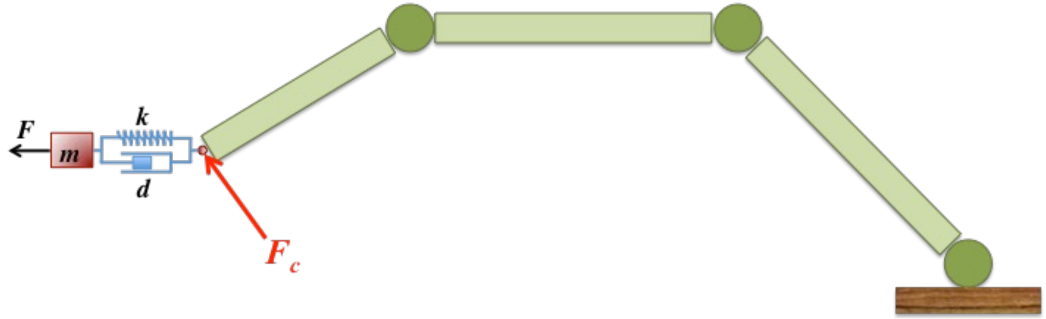
↖ initial contact point position when interaction begins

Impedance-based control of interaction

Reaction to contact forces by generalized impedance —at different levels

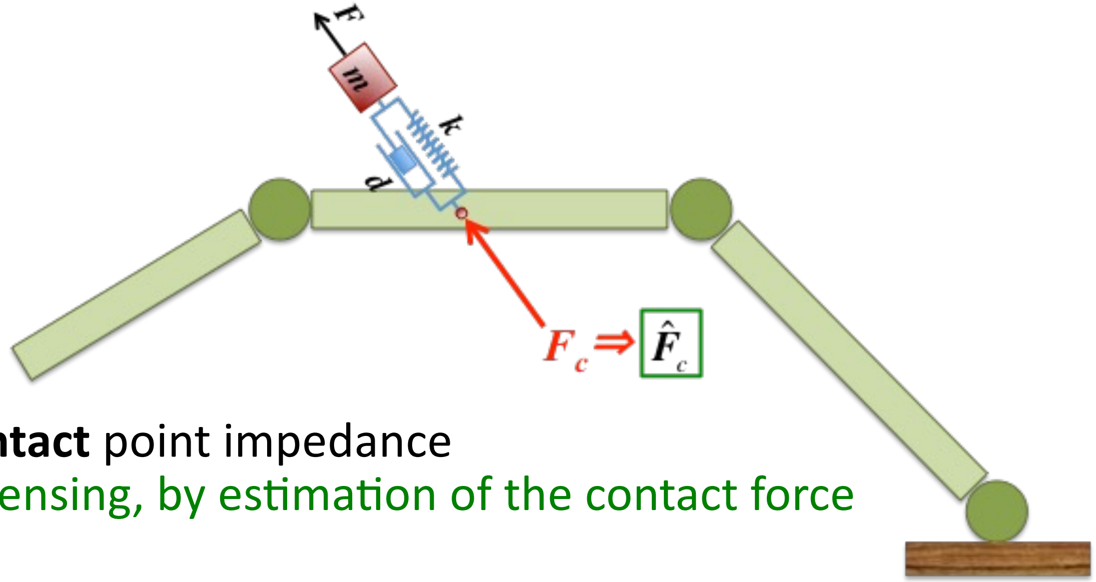
consider a fully rigid robot





Joint impedance
needs joint torque sensors

Cartesian impedance
needs F/T sensor



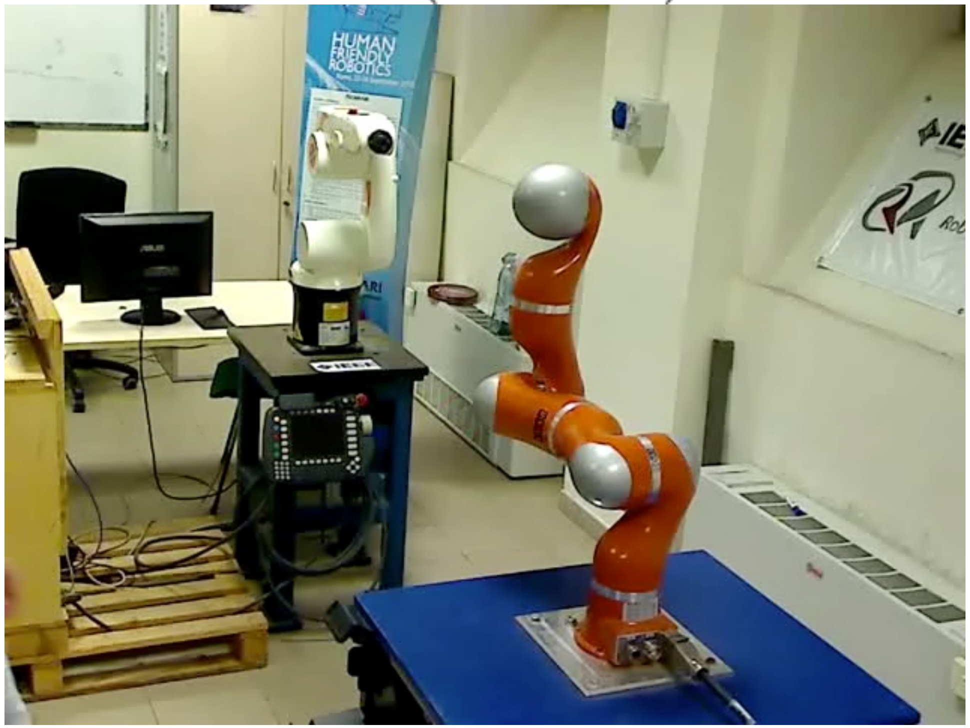
Contact point impedance
without force/torque sensing, by estimation of the contact force

Control of generalized impedance

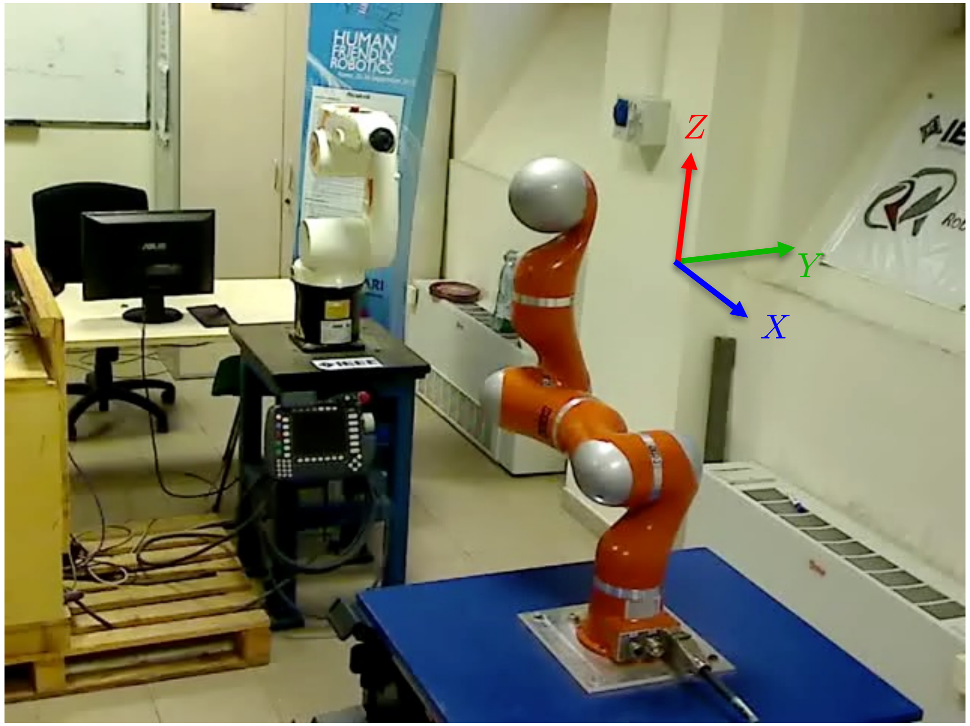
Human-robot collaboration at the contact level (ICRA 2015)

natural (unchanged) robot inertia at the contact

$$M_d = \left(J_c M^{-1} J_c^T\right)^{-1}$$



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



2-part video

https://youtu.be/NHn2cwSyCCo

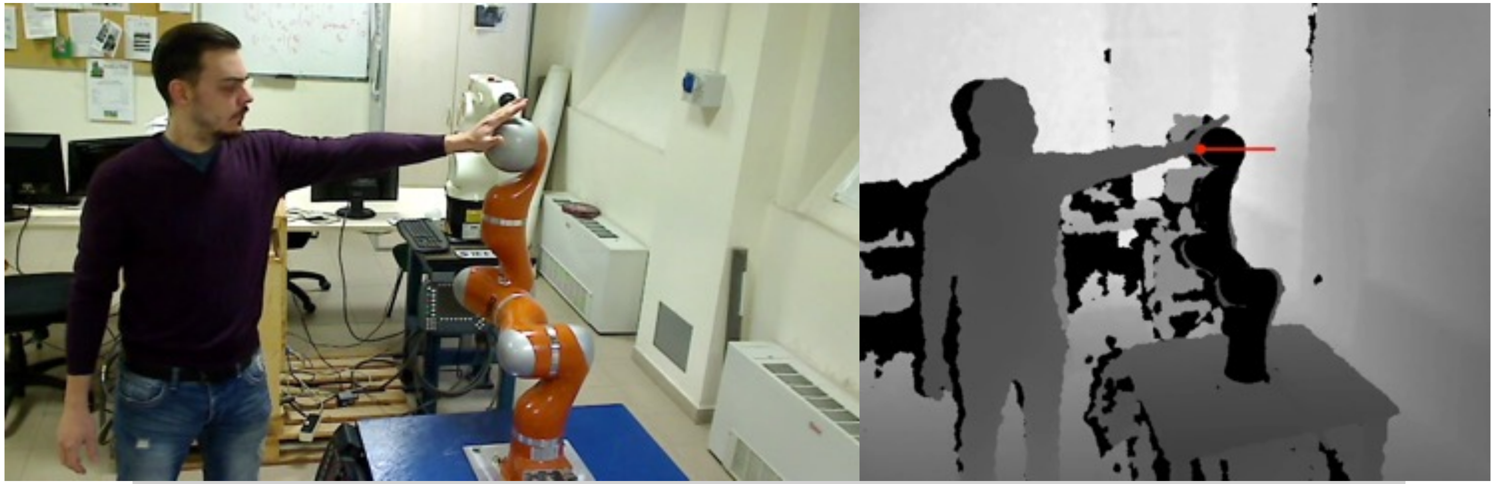
contact force **estimates** are used here
only to detect and localize contact
for starting a collaboration phase

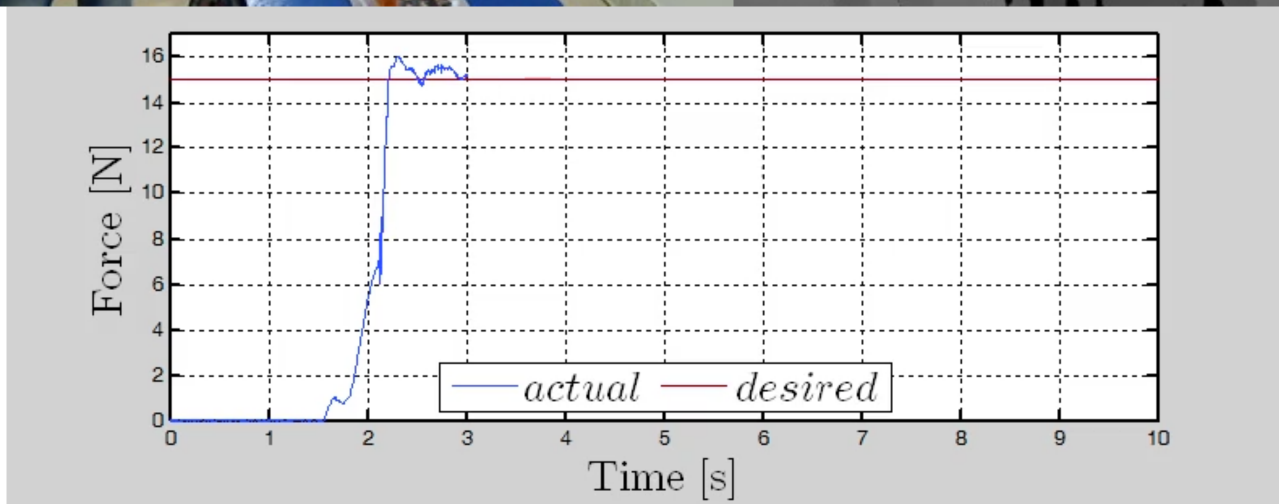
contact force **estimates** used **explicitly** in
control law to modify robot inertia at the contact
($M_{d,X} = 20$, $M_{d,Y} = 3$, $M_{\mathrm{d},Z} = 10$ [kg])

Contact force regulation with virtual force sensing

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

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





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

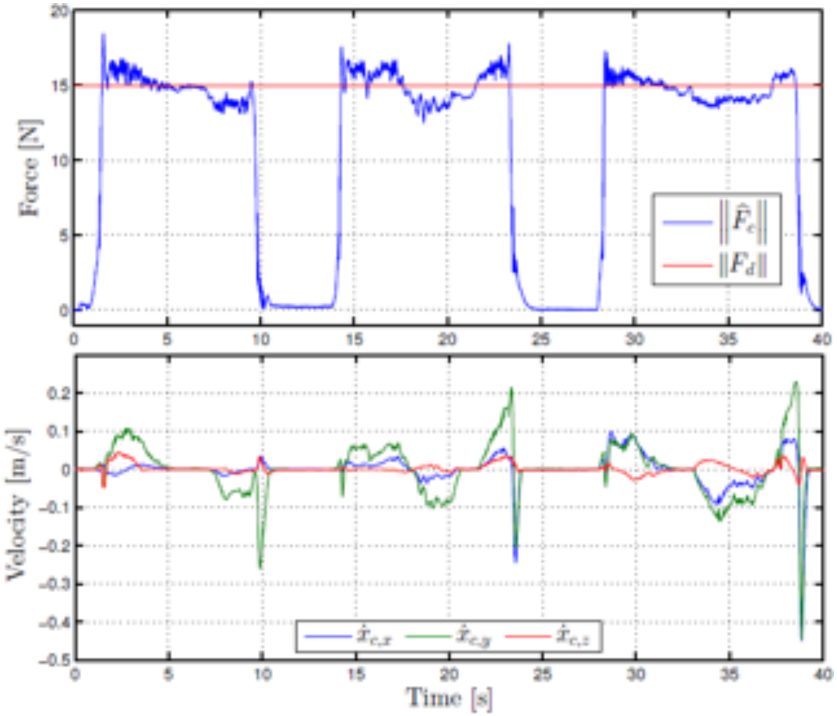
Control of generalized contact force

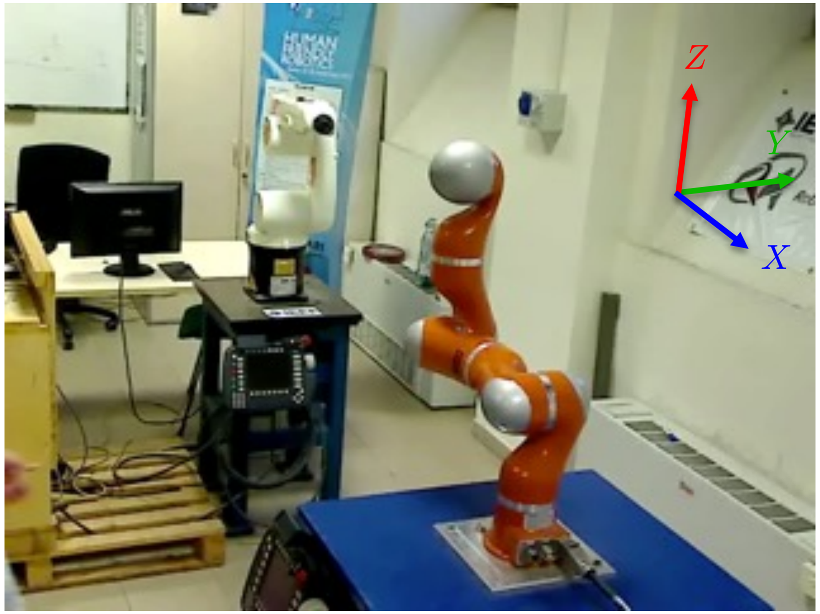
Task-compatible force control scheme (ICRA 2015)

- 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 control law is able to regulate the contact force **exactly**





video

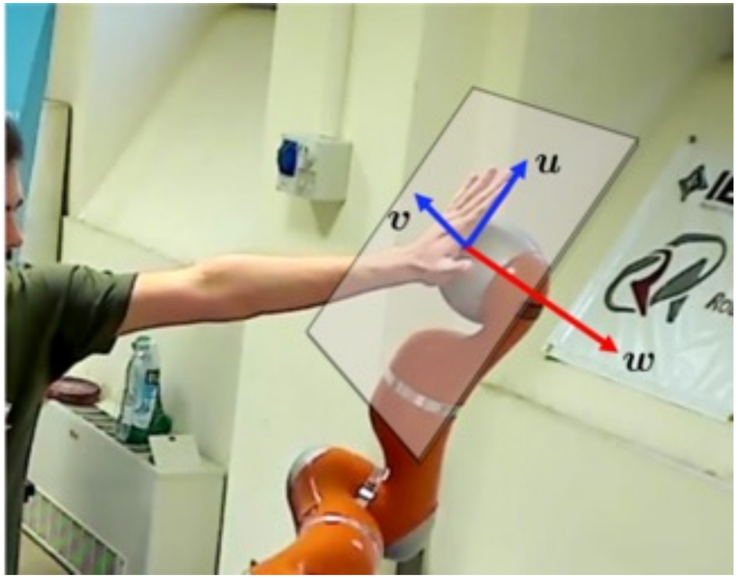
task-compatible control of contact force
https://youtu.be/2X1e2PxwUKo

Collaboration control

Hybrid force/velocity control scheme (ICRA 2016)

- it allows to control **both** contact force and motion at the contact 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** is obtained by a rotation matrix $\boldsymbol{R}_t$ such that $\boldsymbol{z}_t$ is aligned with the **estimated** contact force

$$\boldsymbol{R}_t = [\ \boldsymbol{u} \quad \boldsymbol{v} \quad \boldsymbol{w}\ ] = \left[\ \boldsymbol{u} \quad \boldsymbol{v} \quad \frac{\widehat{\boldsymbol{F}}_c}{\|\widehat{\boldsymbol{F}}_c\|},\ \right]$$



- after feedback linearization with $\boldsymbol{\tau} = \boldsymbol{M}\boldsymbol{a} + \boldsymbol{n} - \boldsymbol{J}_c^T \widehat{\boldsymbol{F}}_c$, the acceleration command is

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

- **complete decoupling** between force control and velocity control can be achieved by choosing the new auxiliary control input $\boldsymbol{a}_c$ using directional selection matrices as

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

Collaboration control

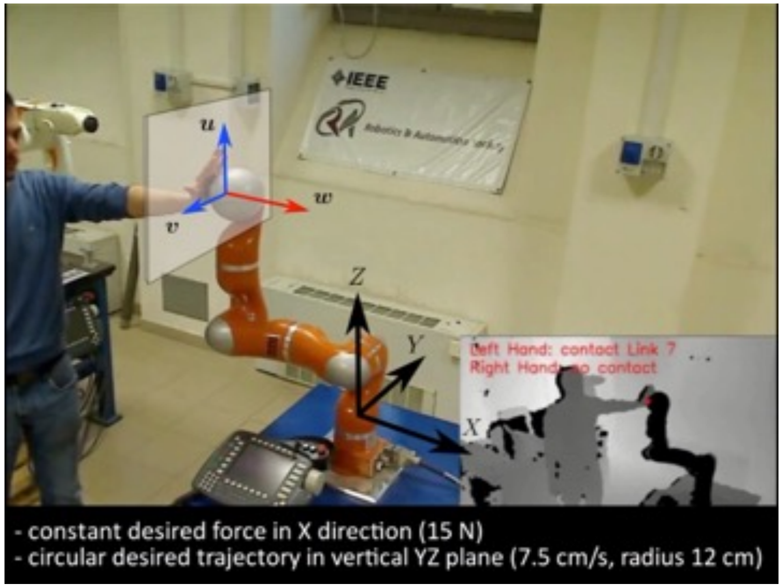
Hybrid force/velocity control at contact level (IROS 2016)

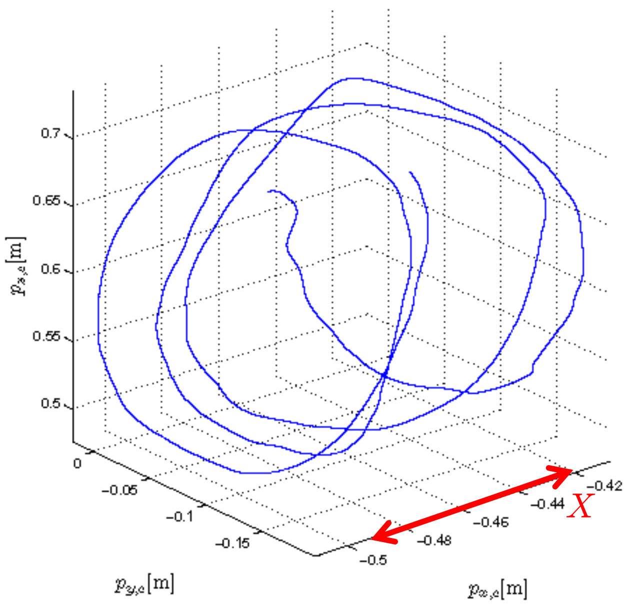
- desired contact force along the X direction regulated to $\boldsymbol{F}_d = 15[N]$
- desired velocity/acceleration to perform a **circle** in the vertical YZ plane

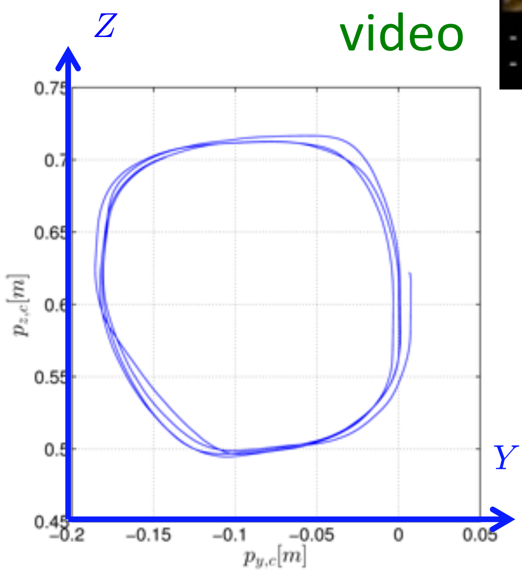
$$\boldsymbol{\nu}_d = \begin{bmatrix} \omega\rho \sin\omega t \\ \omega\rho \cos\omega t \end{bmatrix} \qquad \dot{\boldsymbol{\nu}}_d = \begin{bmatrix} \omega^2\rho \cos\omega t \\ -\omega^2\rho \sin\omega t \end{bmatrix}$$

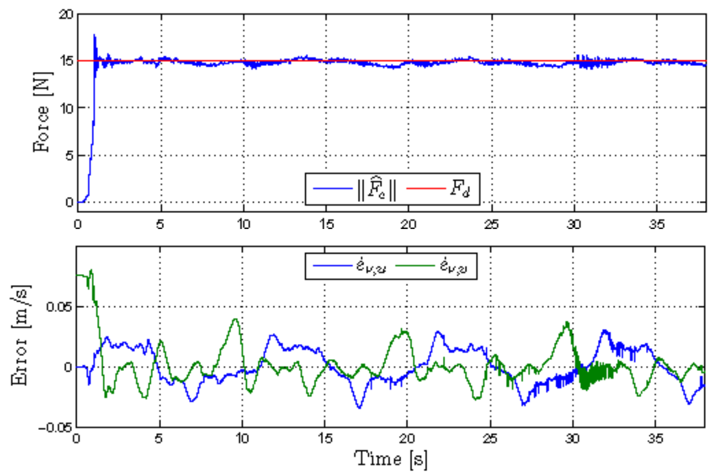
https://youtu.be/tIhEK5f00QU

video





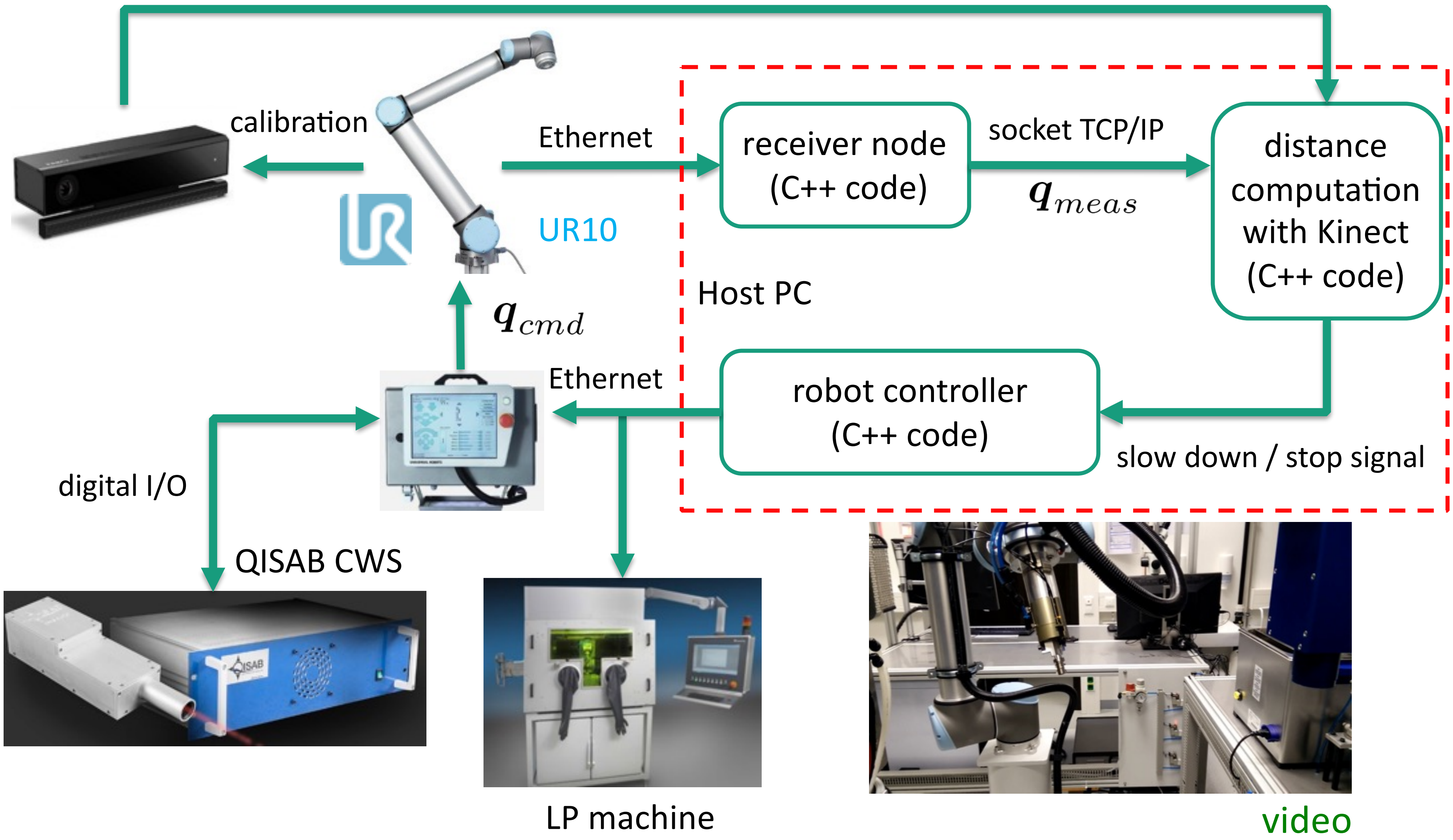




≈ 7 cm of motion in the force-controlled direction

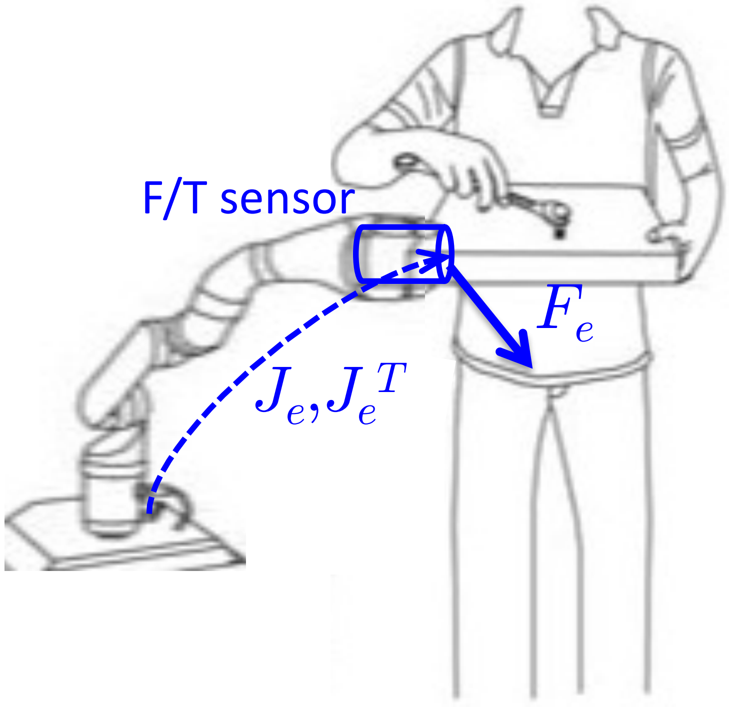
Scenario for HRC in manual polishing

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



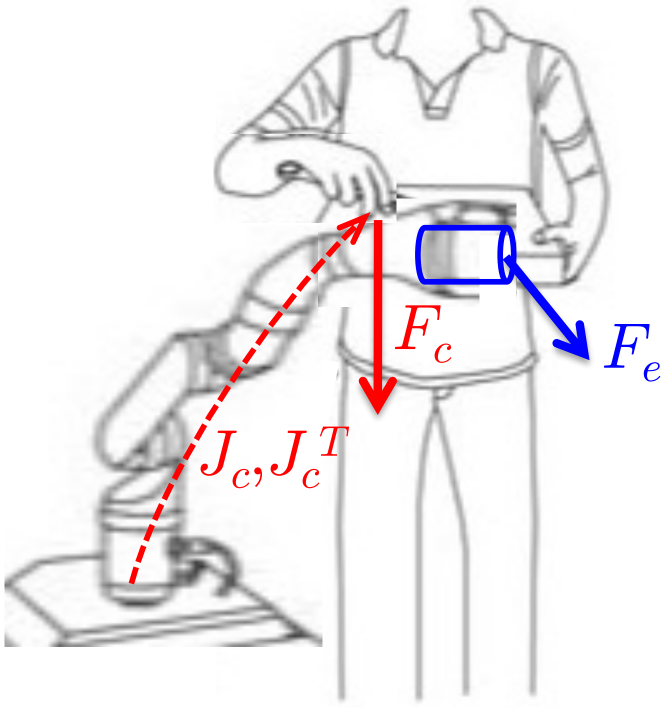
Scenario for HRC in manual polishing

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



Handling multiple contacts

Dynamic model and residual computation using also the F/T sensor

- robot **dynamic model** takes the form

$$M(q)\ddot{q} + \boldsymbol{S}(q,\dot{q})\dot{q} + g(q) = \tau + J_e^T(q)F_e + J_c^T(q)F_c$$

- joint torques resulting from different contacts

(measured) at the end-effector level

$$\tau_e = J_e^T(q)F_e$$

at a generic point along the structure

$$\tau_c = J_c^T(q)F_c$$

- monitor the robot generalized momentum $p = M(q)\dot{q}$

- (model-based) **residual vector** signal to detect and isolate the generic contacts

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

$$K_i \to \infty \text{ (sufficiently large)} \quad \Rightarrow \quad r \simeq \tau_c$$

HR collaboration with UR10 robot

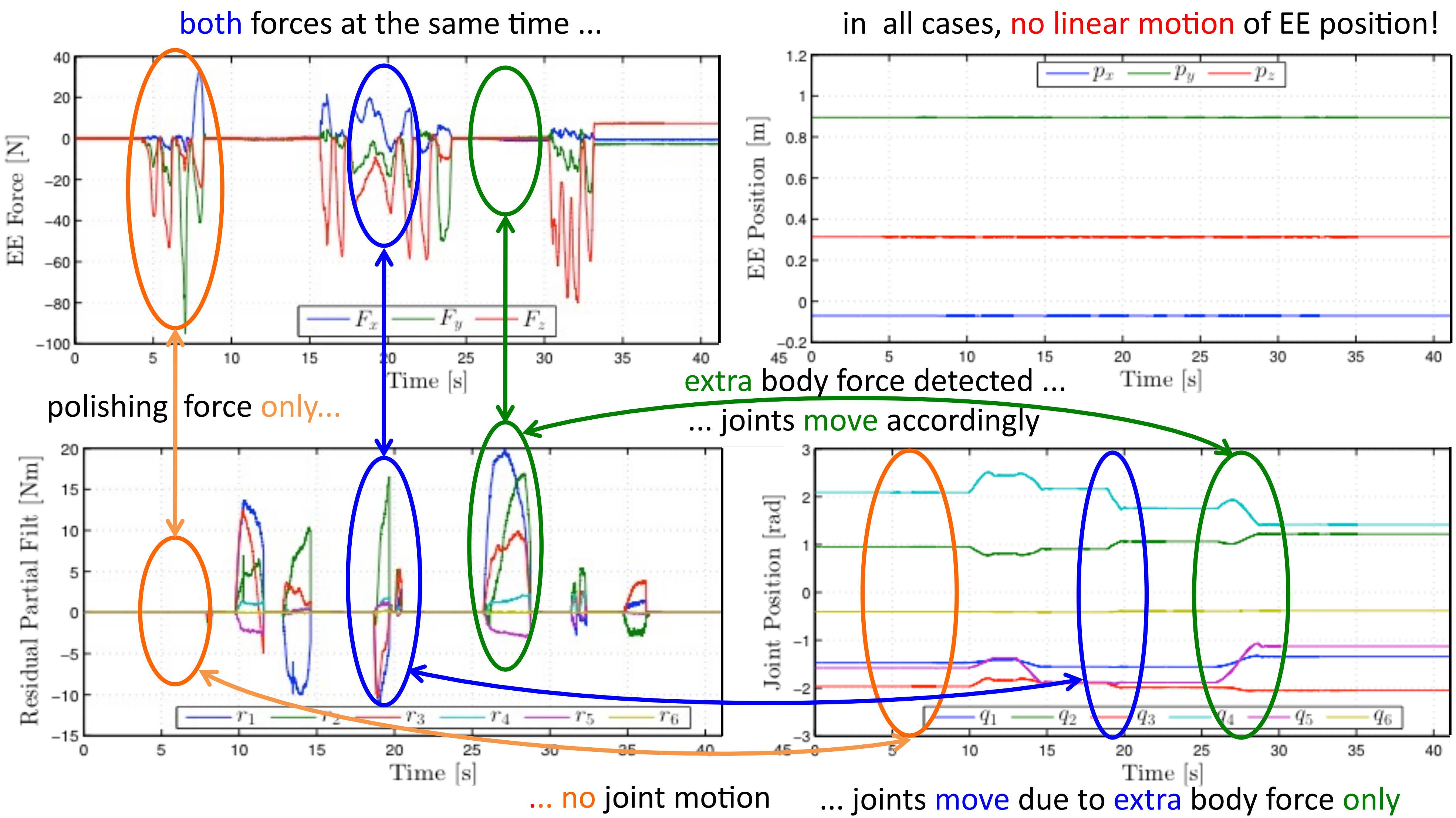
Experimental results (Mechatronics 2018)

video https://youtu.be/bjZbmlAclYk

with F/T sensor, using our residual method

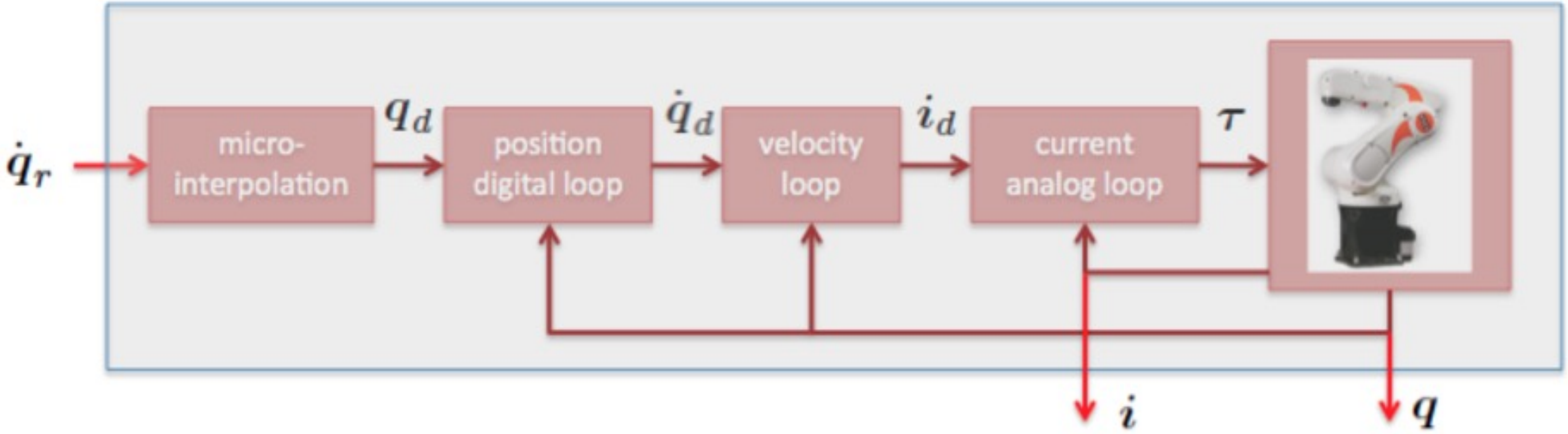
HR collaboration with UR10 robot

Analysis of the experimental results (separating F/T measures from residuals)

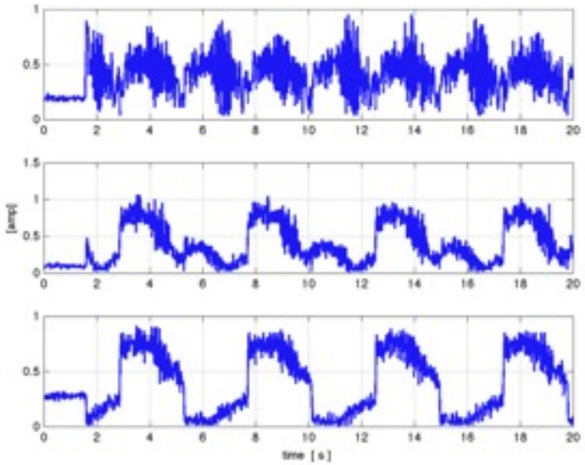


HRC under a closed control architecture

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 (∝ motor torques)
- the only user commands for the controller are velocity or position references in joint (or Cartesian) space

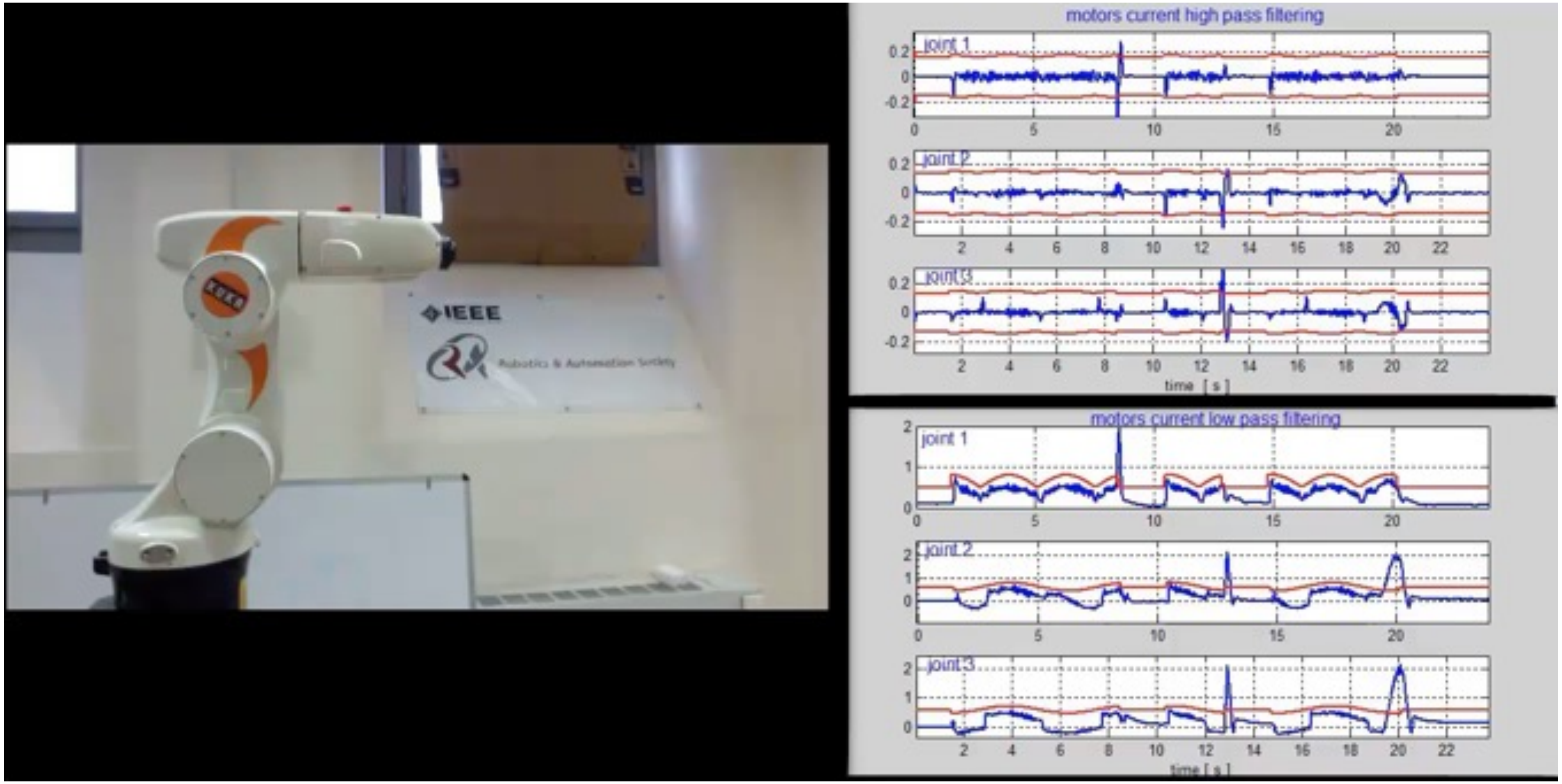


typical motor currents on first three joints

Distinguish accidental collisions from intentional contacts

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

video http://youtu.be/18RsAxkf7kk



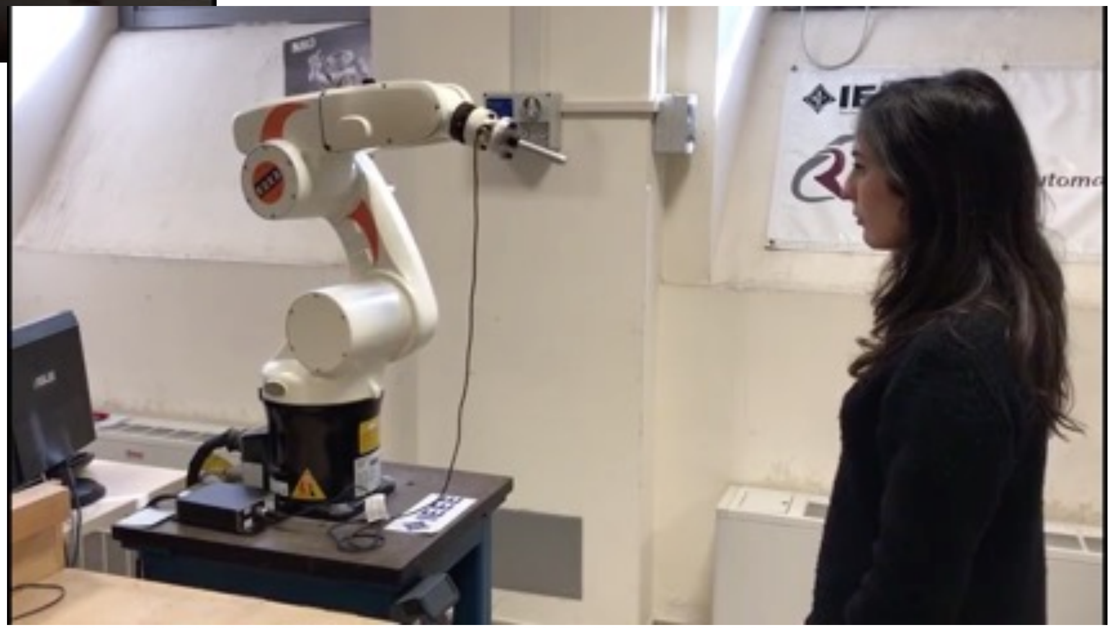
using high-pass and low-pass filtering of motor currents
— here collaboration mode is manual guidance of the robot

Combining motor currents and F/T sensor data

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

2-part video

https://youtu.be/SfZcG1Y713w



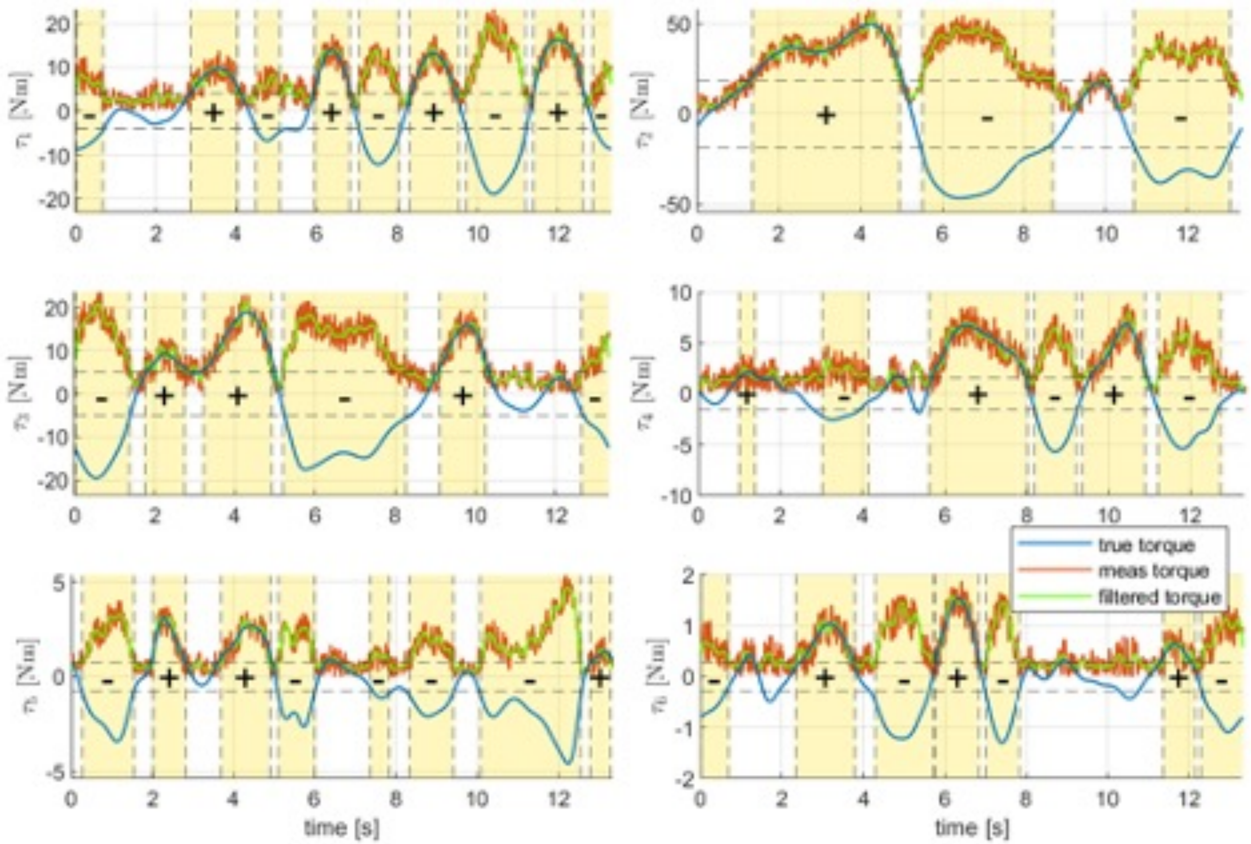
interaction may occur
at the **end-effector**,
on the **robot body**, or on **both**

Dynamic modeling of KUKA KR5 Sixx R650

Using a method to identify the (unknown) signs of measured motor currents (I-RIM 2021)

simulation test

39/39 segments of motor currents correctly handled (assign right +/-)

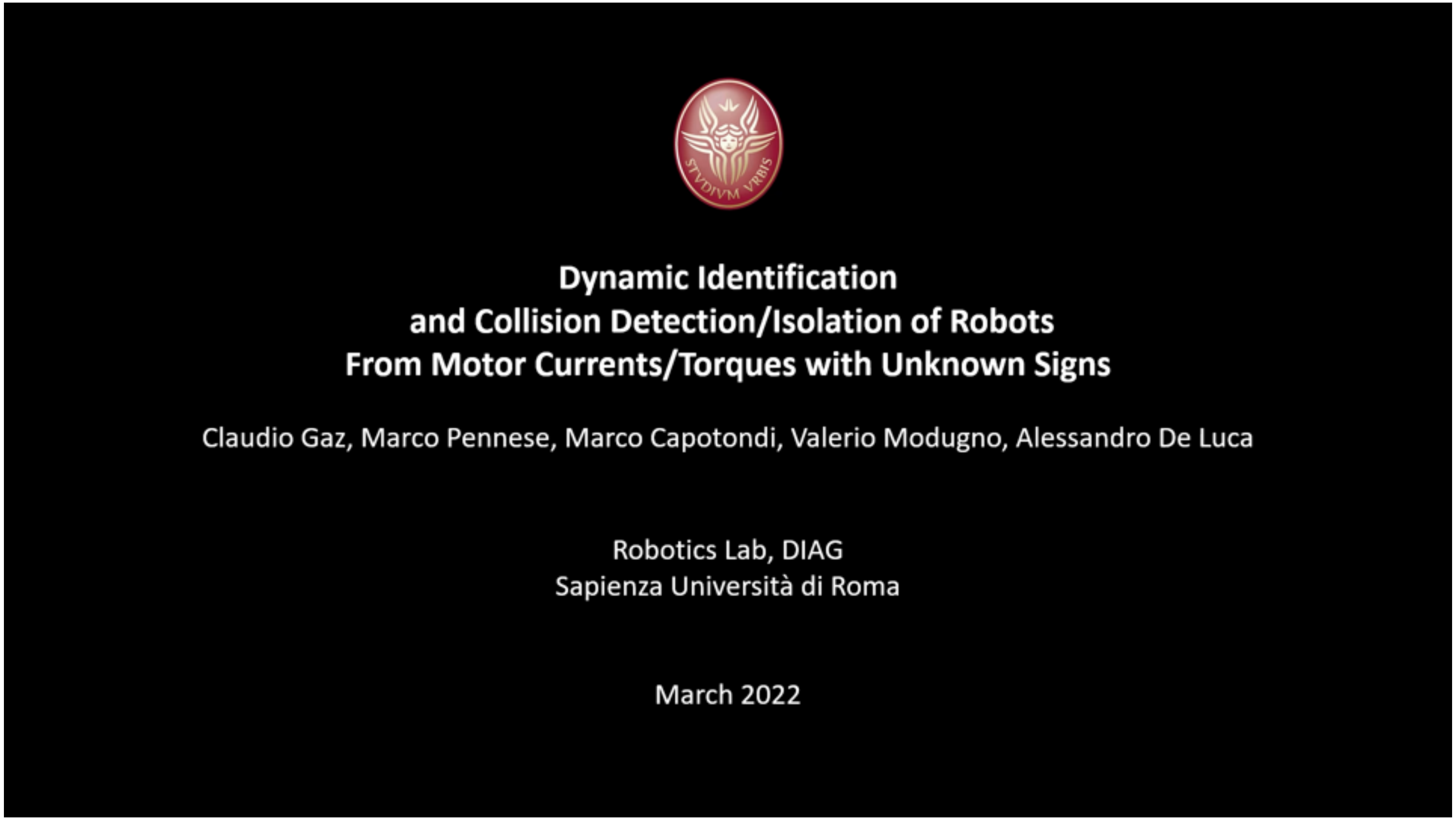


- identify signs of motor currents by means of a Tree Penalty-Based Parameter Retrieval algorithm
- use the method in experimental identification of robot dynamic model, followed by validation tests

Collision detection and isolation

Even on a KUKA KR5 Sixx R650 with closed control architecture (in 2022)

$$\sigma_{mod}(t) = k_\sigma \int_0^t [\hat{\boldsymbol{\pi}}^T \boldsymbol{Y}^T(s)\boldsymbol{Y}(s)\hat{\boldsymbol{\pi}} - \boldsymbol{\tau}^T(s)\boldsymbol{\tau}(s) - \sigma_{mod}(s)]\, ds$$



video

use of extra residual for motor currents of a priori unknown signs

Conclusions

Take-home messages

- 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, flexible link 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 not covered (or ahead)
  - human motion and intention prediction, merging models and data
  - integration with AI-based cognitive HRI modules to increase robustness
  - use of residuals for continuum soft robots, especially for interaction control

Our team at DIAG

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

PhD + master students

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@Stanford – AI Lab - Oussama Khatib, Torsten Kröger

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