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Safety for Human-Robot Interaction in Industrial Settings
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Physical human-robot collaboration: Sensing, monitoring, and control issues

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Motivation

Research solutions and open questions

- can physical Human-Robot Collaboration (pHRC) tasks be "safe" in general?
- how far can we go down the safety line in pHRC by using the latest robotic technologies (including sensing and control)?
- what problems do researchers face when transferring in industrial settings recent technical/scientific results in pHRC?

⇒ like some of the methods experienced with SAPHARI

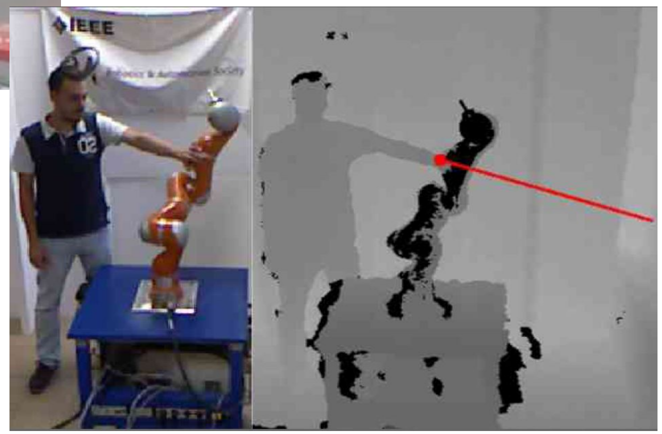
- collision handling and robot reaction
- workspace monitoring
- distinguishing intentional human-robot contacts from collisions
- human-robot coexistence
- controlling whole-body exchanged contact forces

Collision avoidance and contact handling

Basic safety-related control problems in pHRI

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

continuous
collision avoidance
(while the task is running)

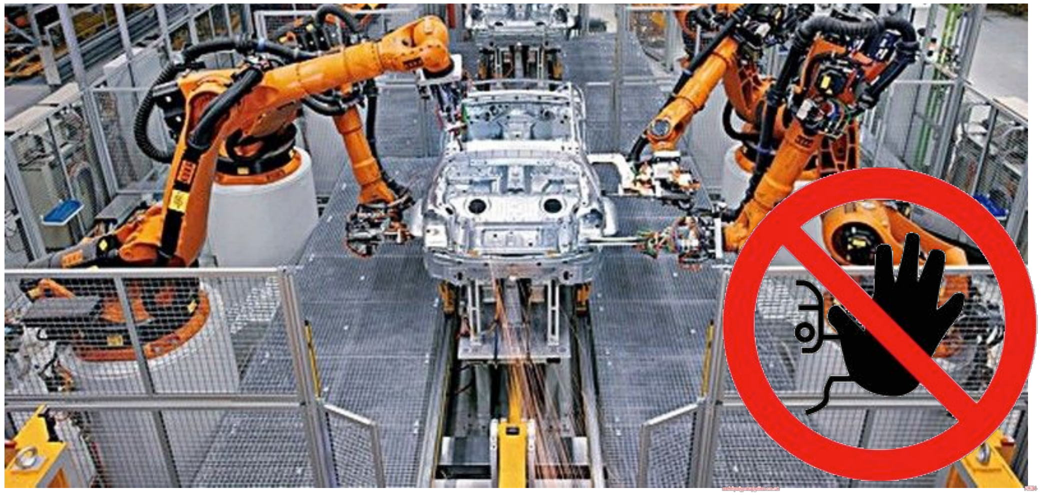


estimation and control
of intentional forces
exchanged at the contact
(**without** force or touch sensors)

Safety

Safety is the most important feature of a robot that has to work close to human beings

Classical solutions preserving safety in industrial environments (cages, fences, stop/slow down robot motion in presence of humans) may not be appropriate for **collaborative pHRI** (= **pHRC**)

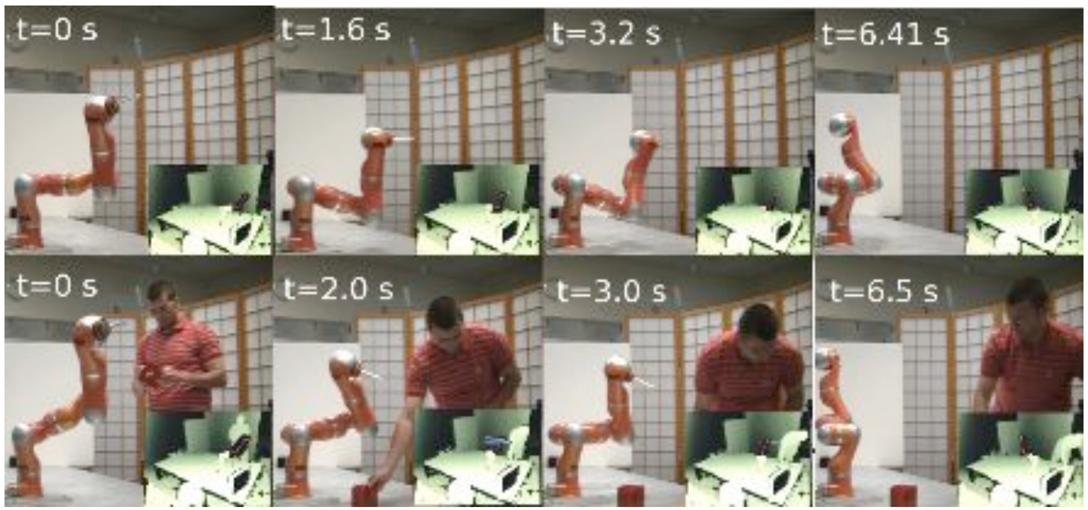


Safety

Coexistence

Coexistence is the robot capability of sharing the workspace with other entities, most relevant humans

Human (**and robot!!**) safety requirements must be consistently guaranteed (i.e., **safe coexistence**)



original robot task

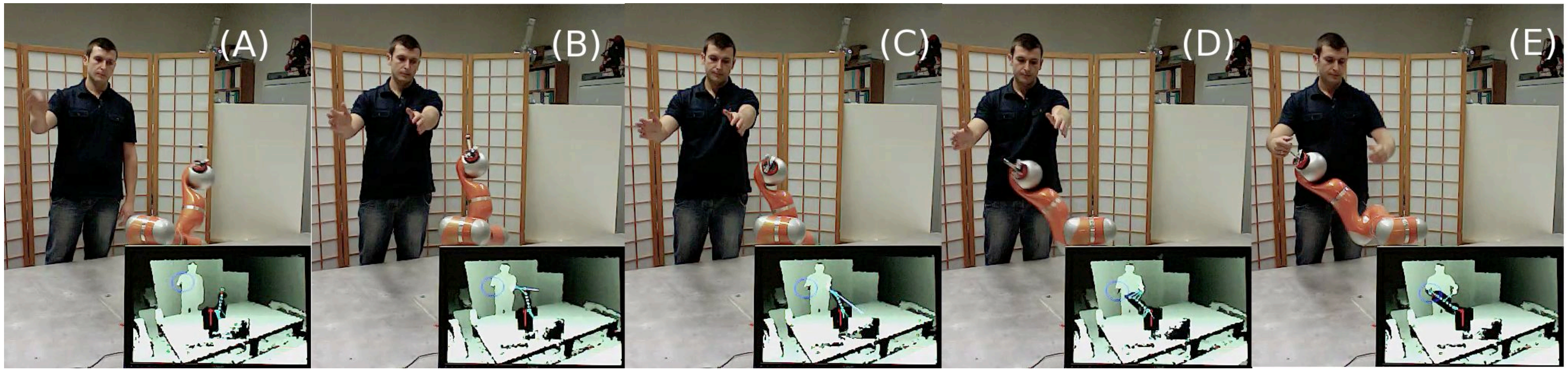
safe HR coexistence

Control architecture for physical HRI

Hierarchy of consistent behaviors (BioRob 2012)

Collaboration occurs when the robot performs complex tasks with direct human interaction and coordination

Two modalities which are not mutually exclusive: *contactless* and *physical*



Safety in collaborative robot operation

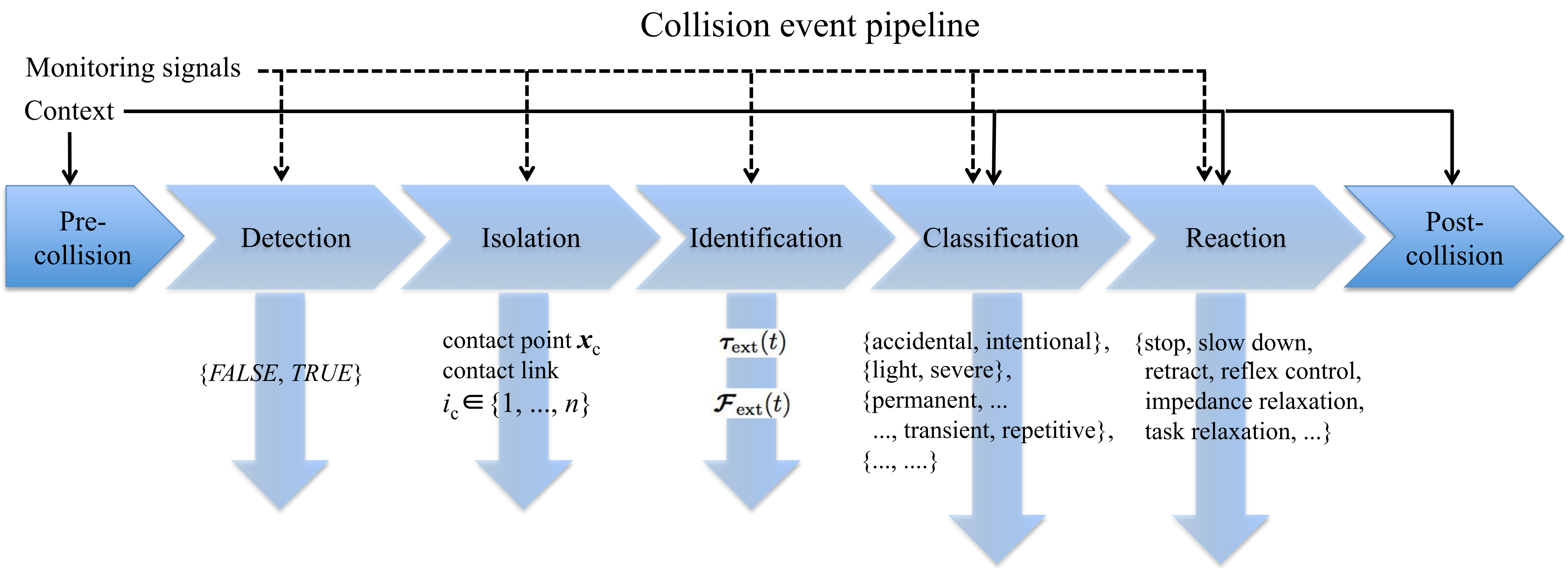
According to ISO 10218-1 (more on this also in TS 15066)

	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

CWS = Collaborative Work Space RA = Risk Assessment

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 the most suitable decision

Monitoring robot collisions

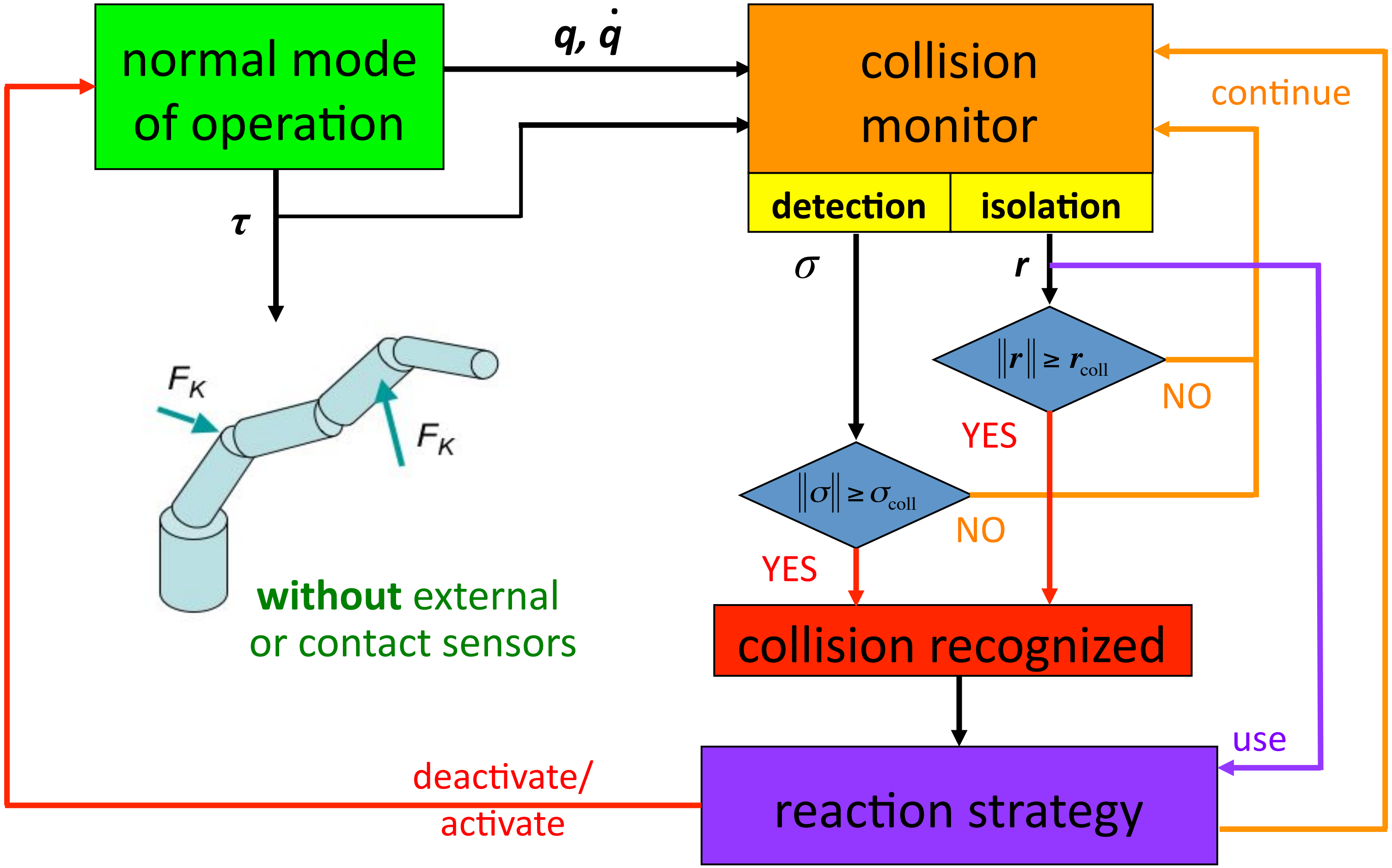
Applies equally to **rigid and elastic** joints, **with and without** joint torque sensing

residual vector

$$r = K_I \left(M(q)\dot{q} - \int_0^t \left(\tau + C^T(q,\dot{q})\dot{q} - g(q) + r \right) ds \right)$$

τ_J

$$\tau_J = K(\theta - q)$$



Collision detection and reaction

Residual-based experiments on DLR LWR-III (dates back IROS 2006)

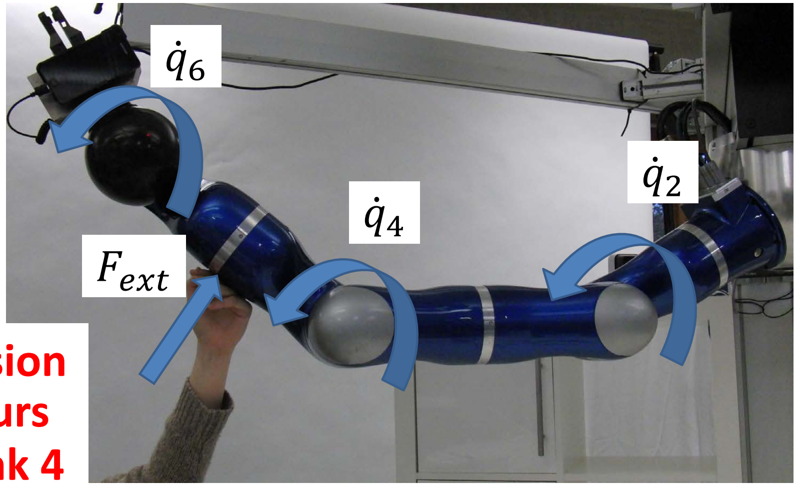
- collision detection followed by different reaction strategies
- zero-gravity behavior: gravity is always compensated first (by control)
- detection time: 2 ms, reaction time: + 1 ms

videos

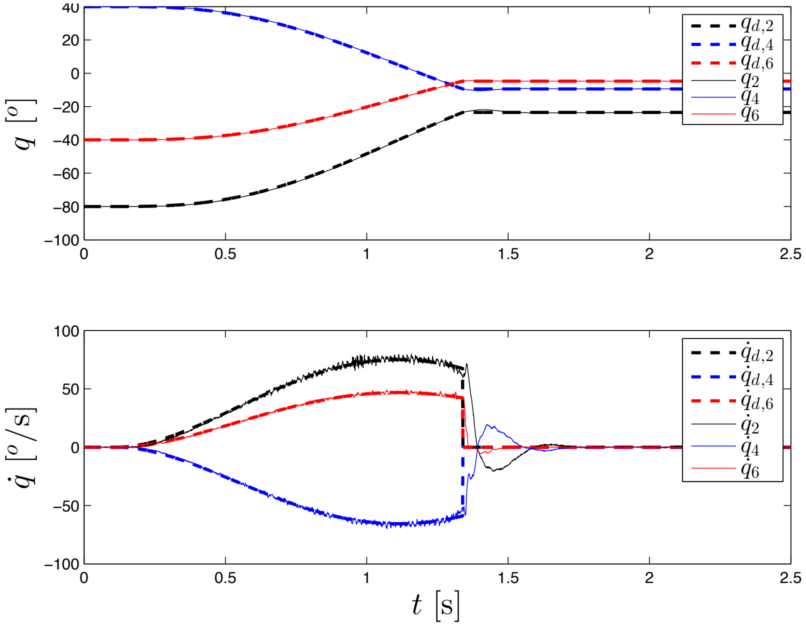
admittance mode	reflex torque	reflex torque
first impact at 60°/s		first impact at 90°/s
$\dot{q}_r = K_Q r$	$\tau = K_R r$	

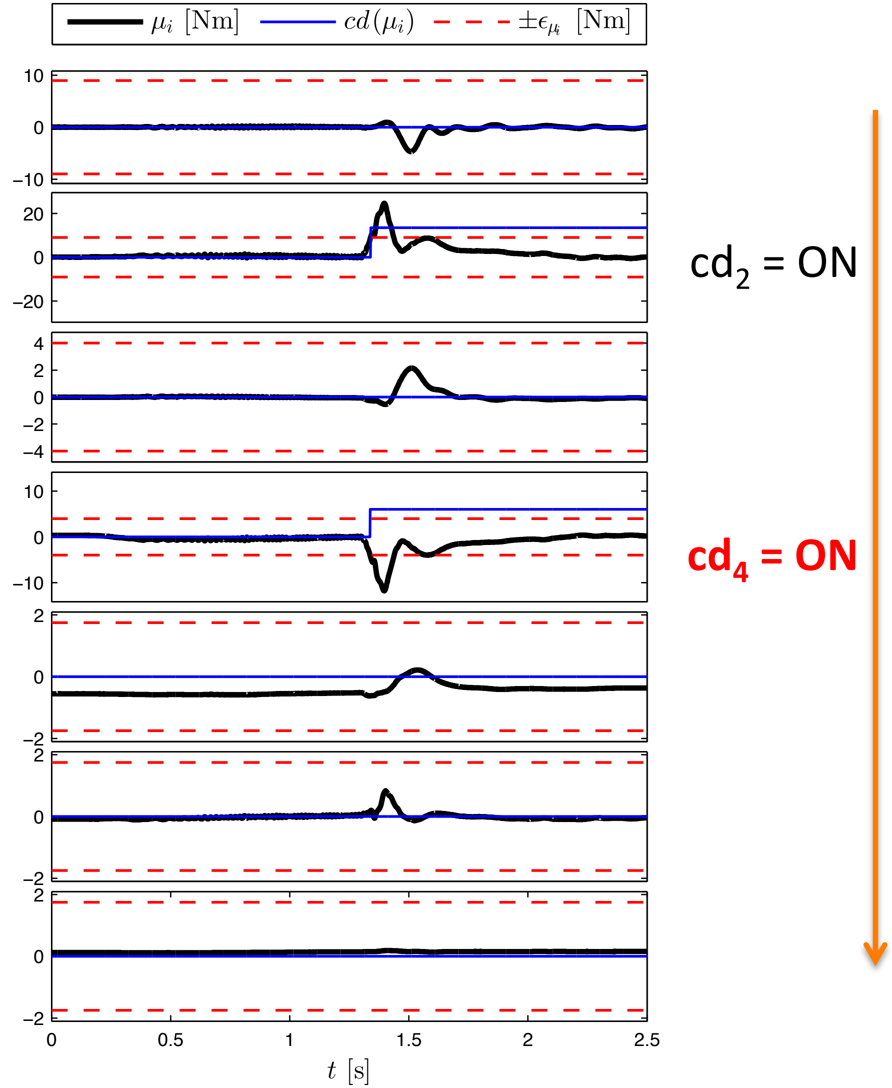
Collision isolation with the residual-based method

Experiment on three moving links of DLR LWR-III under position control



collision occurs at link 4

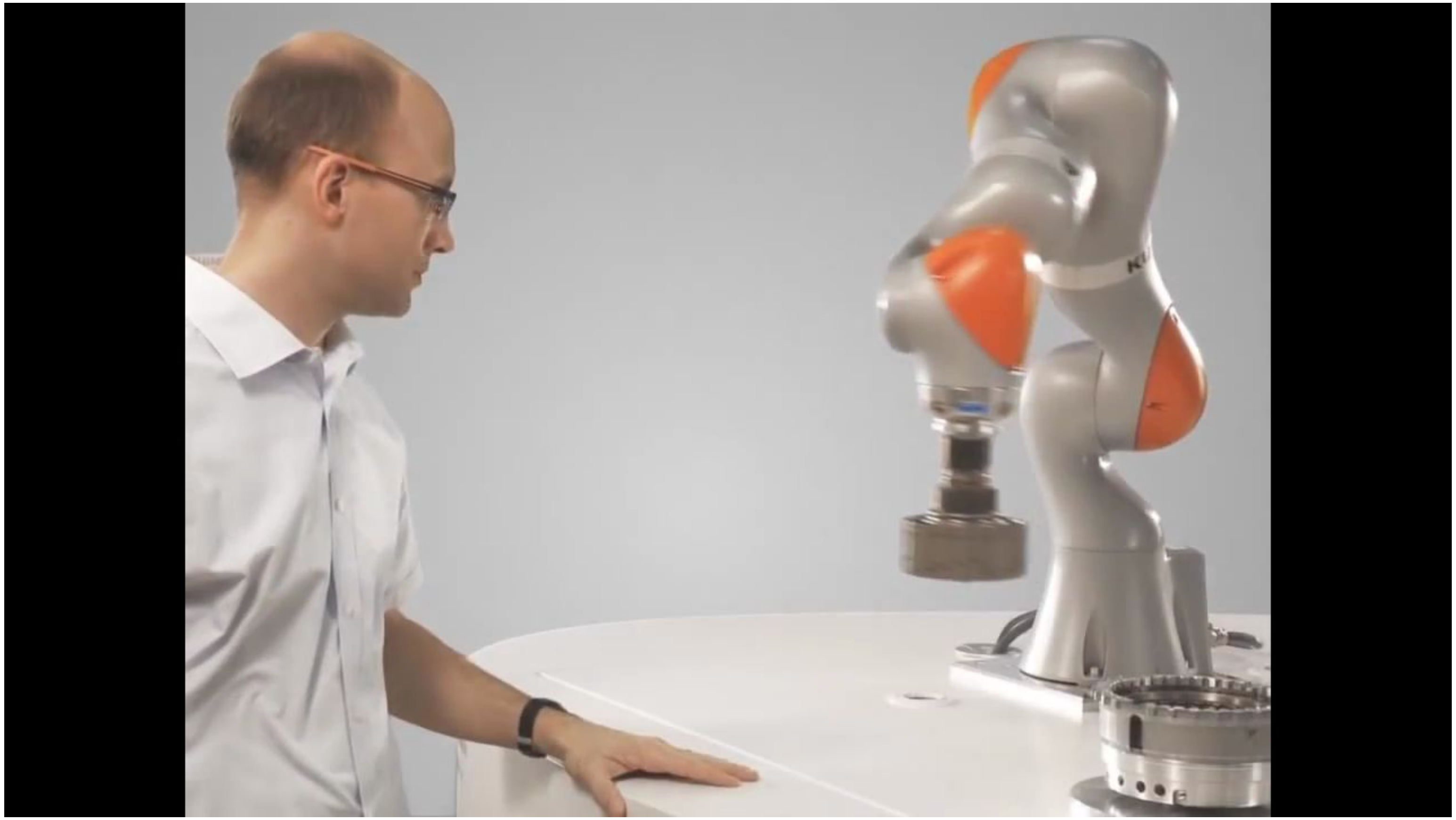




Collision detection

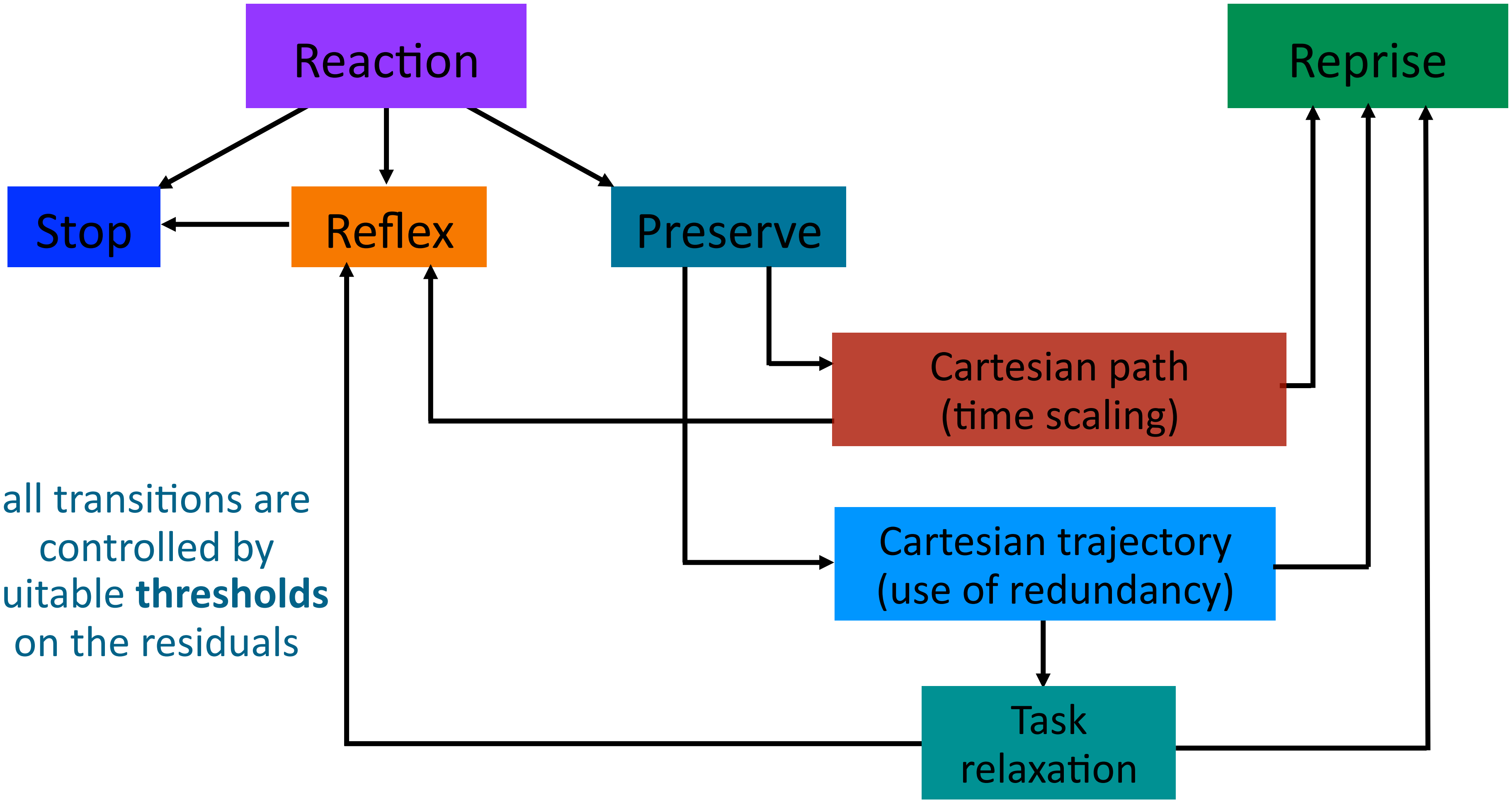
Feature added in the industrial KUKA iiwa robot (in 2013, 7 years later...)

video



only a "**stop!** and then **float**" robot reaction ...

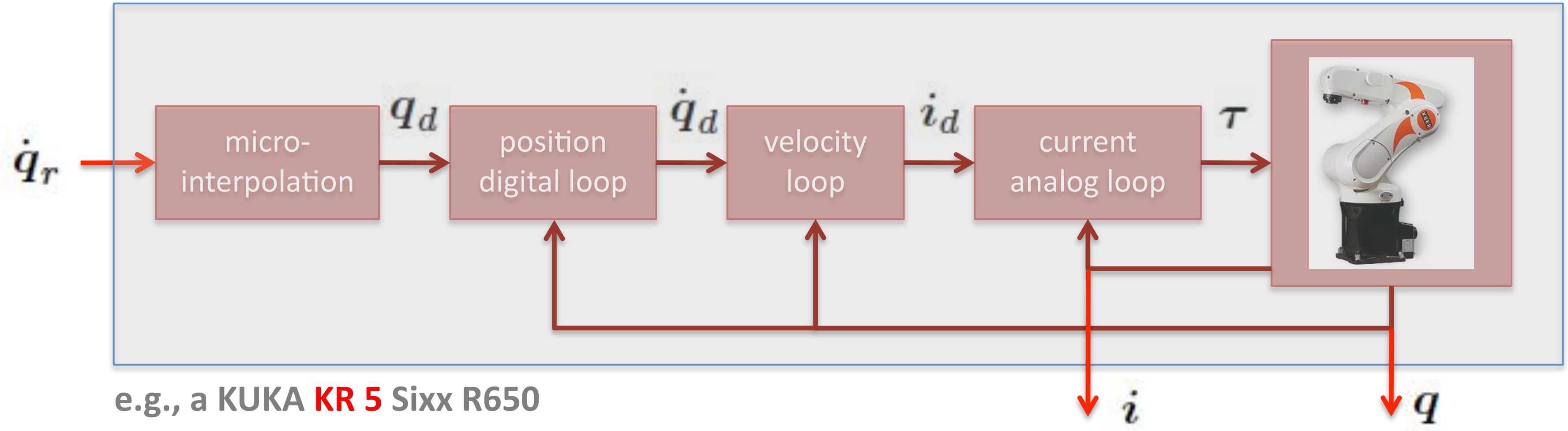
residual amplitude ∝ severity level of collision



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

What can be done with conventional industrial robots?

Closed control architecture and little/no further information



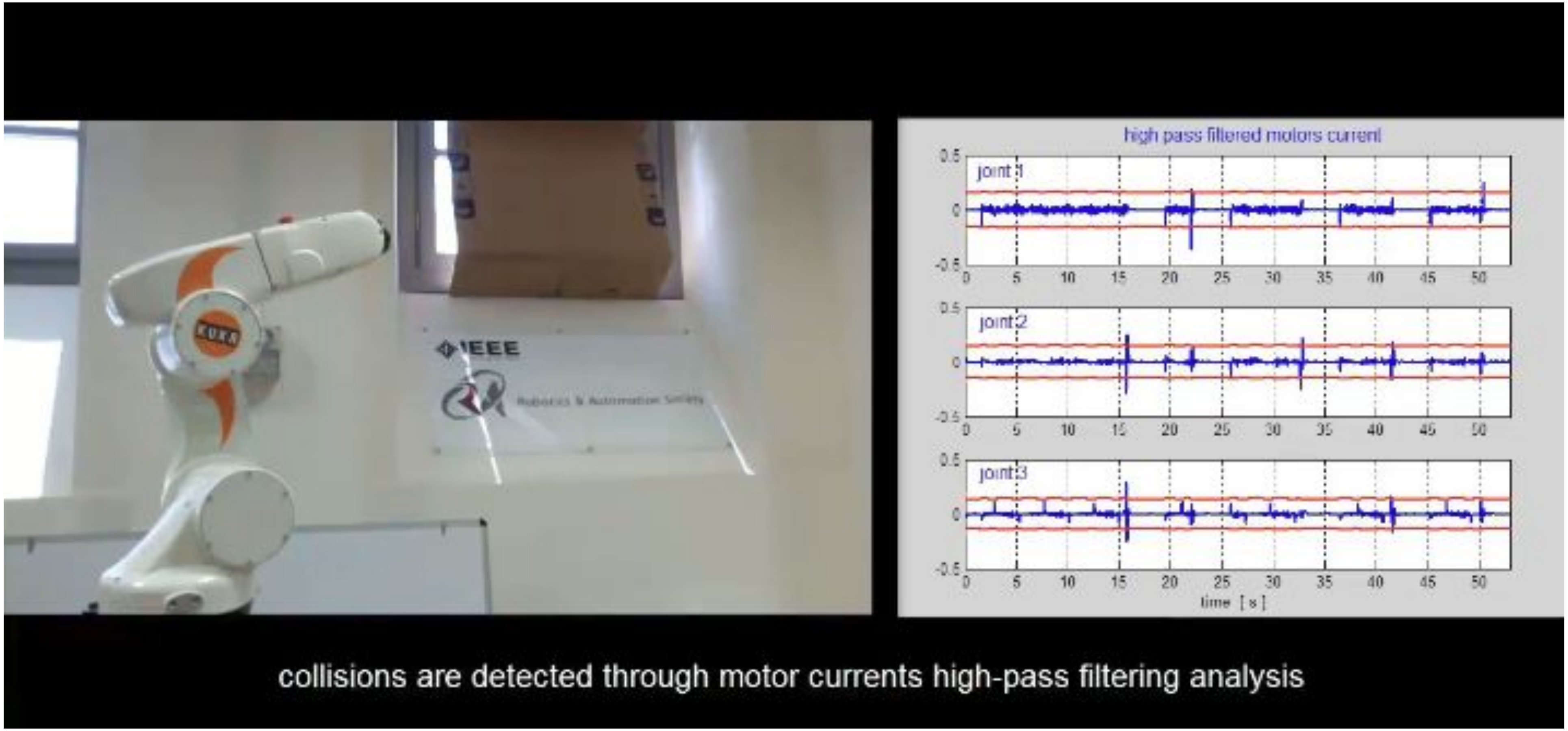
e.g., a KUKA KR 5 Sixx R650

- users can update the external reference velocity (but only every 12 ms, via RSI), based on encoder and motor current readings + external sensor information
  - no torque or current command can be imposed by the user
  - no joint torque sensing available
  - no information on the dynamic model
  - no access to (nor knowledge of) the low-level controllers
- we rely on some "good" properties of (P/PD/PID) joint position controllers ...

Detect collision and stop

Simplest robot reaction strategy for safety (ICRA 2013)

video

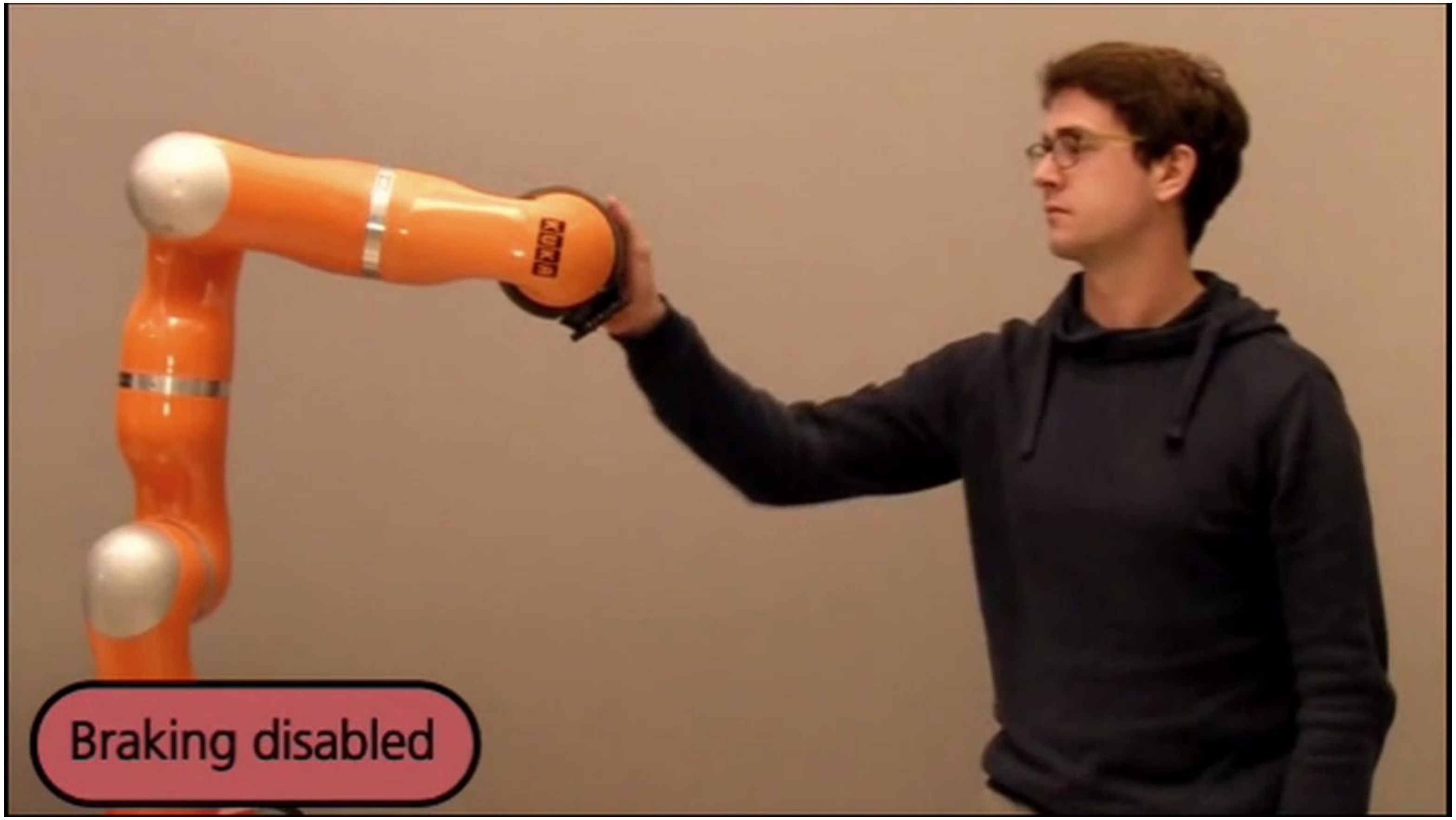


high-pass filtering of motor currents (a signal-based detection...)

How fast can you stop your robot?

Robot "braking" is needed to anticipate an accidental contact

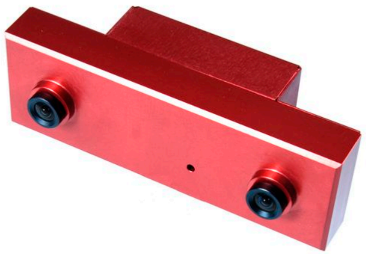
- lightweight is good, however joint compliance should be used carefully!

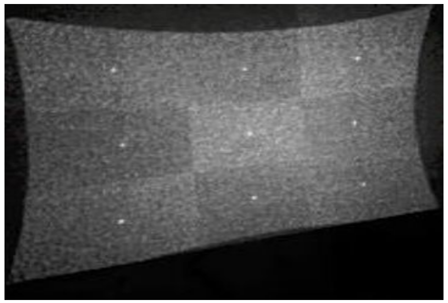
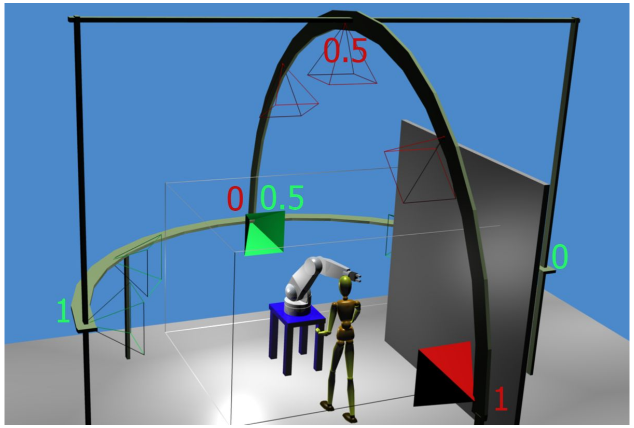


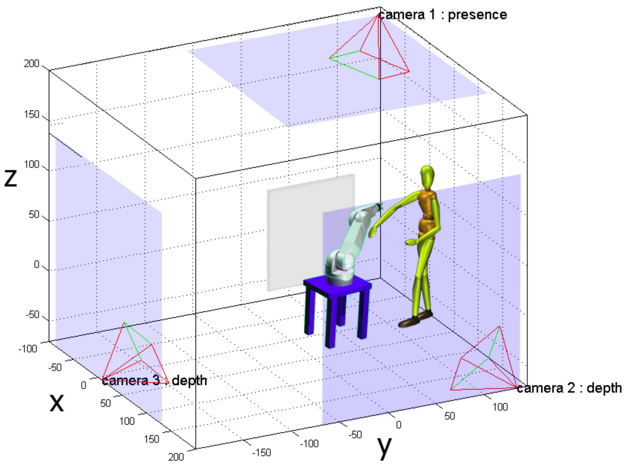
Collision avoidance

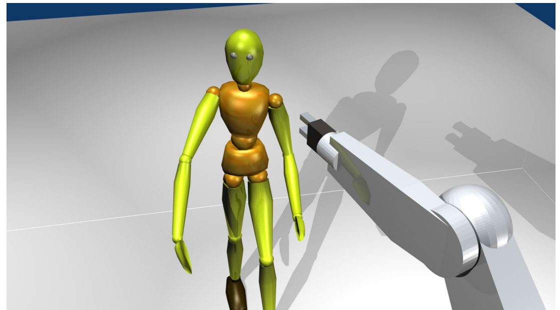
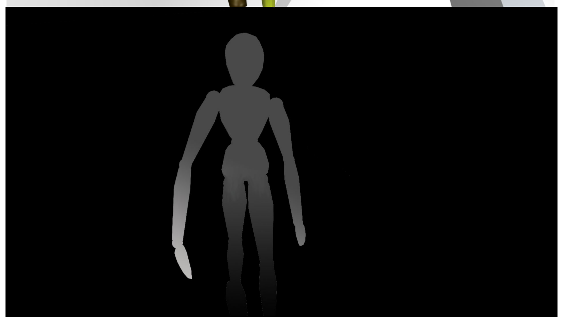
Using exteroceptive sensors to monitor robot workspace (ICRA 2010)

- **external sensing:** stereo-camera, TOF, structured light, **RGB-Depth**, laser, presence, ... placed optimally to minimize occlusions (robot to be **removed** from image/field of view)



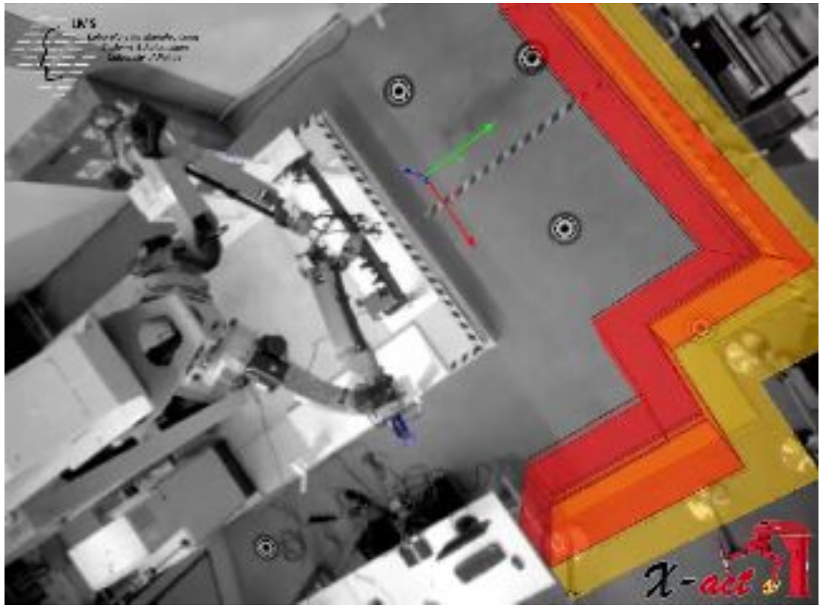





Monitoring the workspace

Bounding boxes on forbidden areas and/or around humans



SafetyEYE by Pilz
in **X-act** EU FP7 project

but

- limited mixing/merging of shared workspaces
- forbidden zones do not “embrace” robot and human dynamically
- problems with more restricted working areas

Politecnico Milano severity indices for speed reduction, evasive motion or task interference

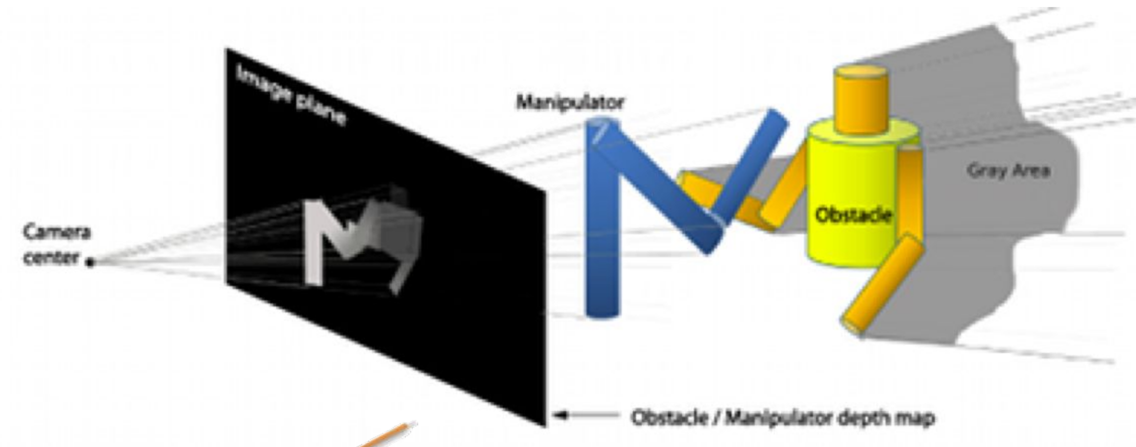
Depth space

2 ½ space for efficient robot-obstacle distance computations (ICRA 2012)

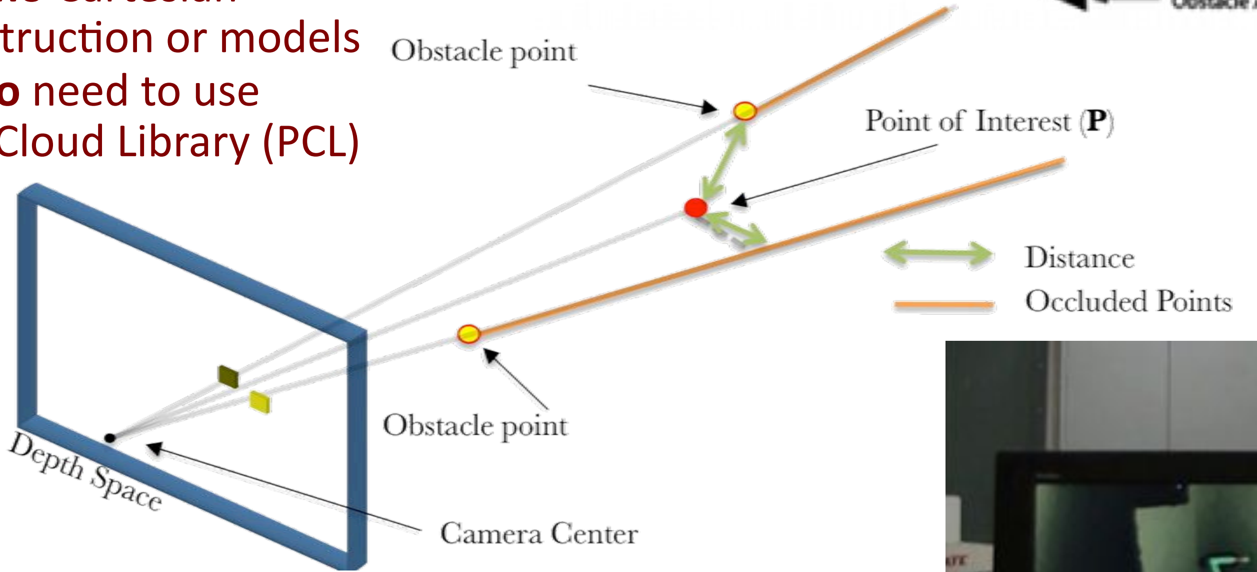
$$p_x = \frac{x_C f s_x}{z_C} + c_x$$

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

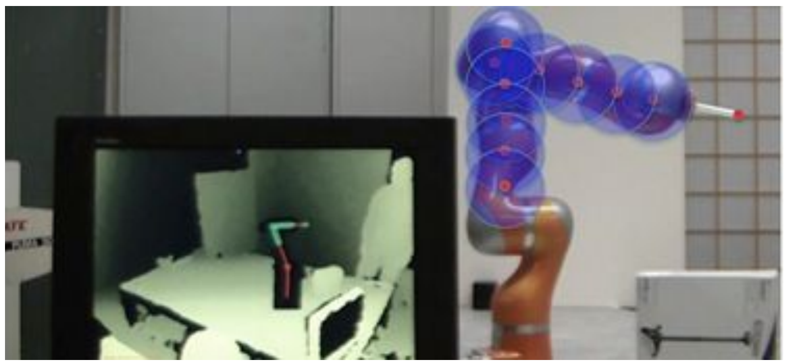
$$d_p = z_C$$



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

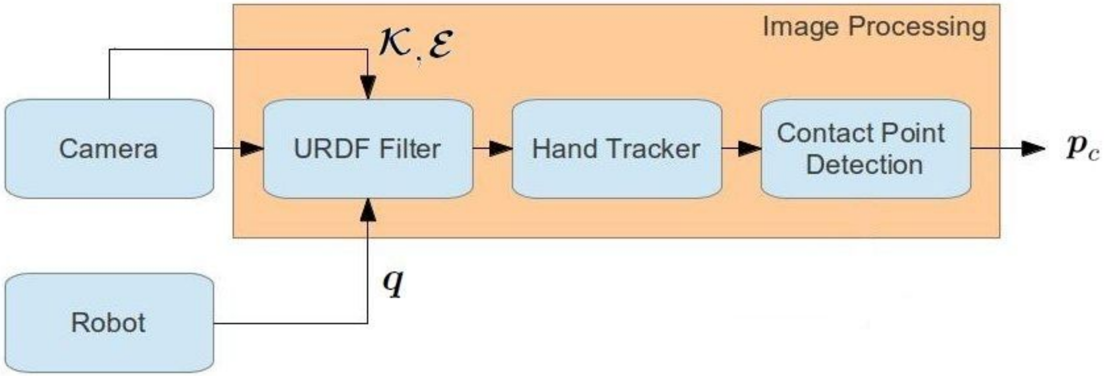


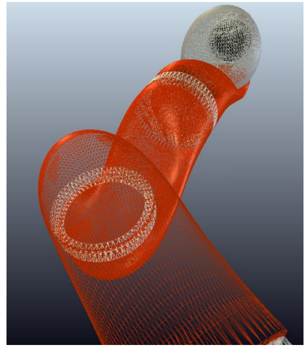
use then, e.g., with artificial potentials for **collision avoidance**



Distance and contact estimation in real time

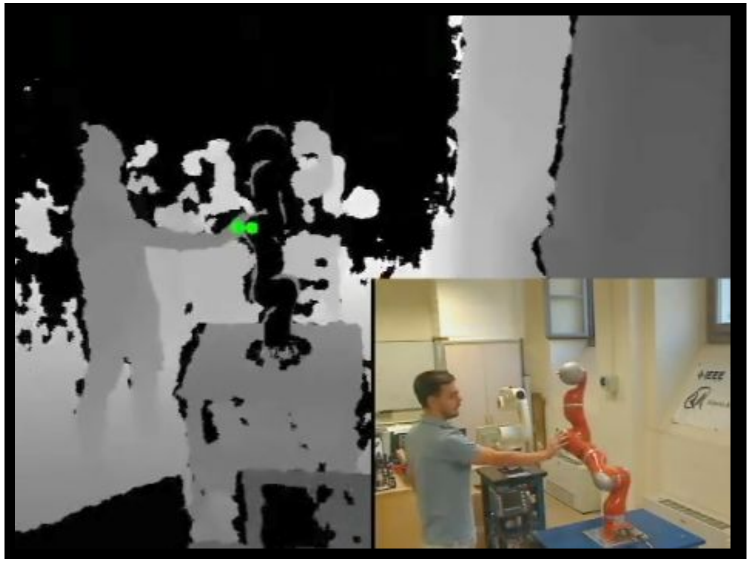
Between points of interest on the robot and human parts or obstacles



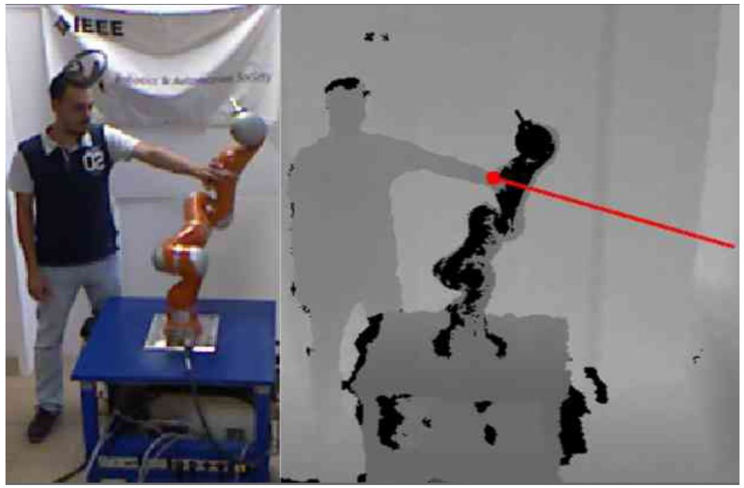


robot surface CAD model

video



minimum distance algorithm runs in parallel for left and right hand (or other body parts)



also for contact force estimation ...
(at **zero** distance)

Safe physical human-robot collaboration

Extracts from long video at IROS 2013

coexistence through
continuous collision avoidance

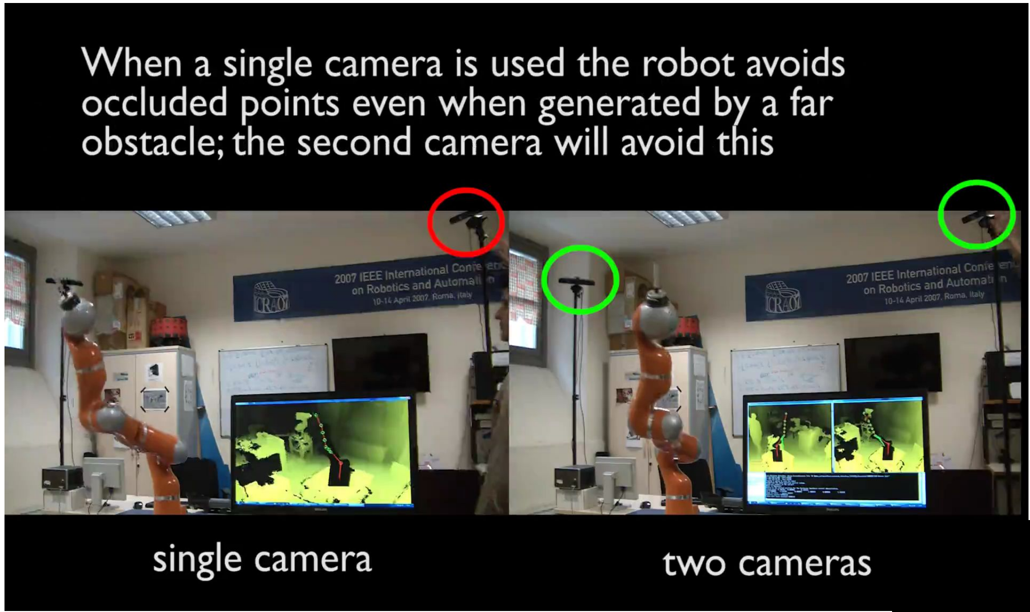
video

video

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

Monitoring workspace with 2 Kinects

Submitted to RA-L/ICRA 2016



video

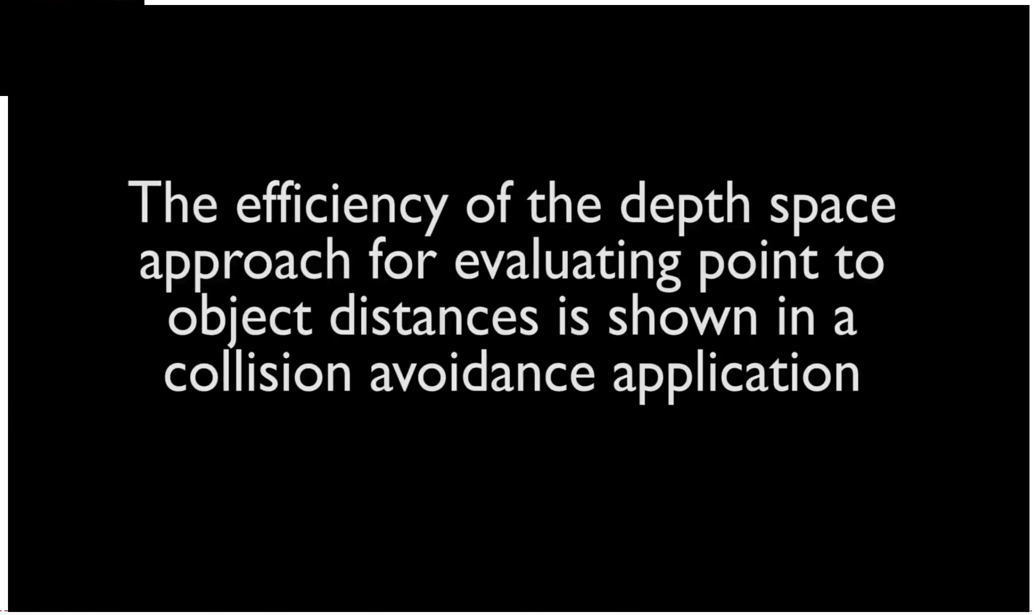
real-time efficiency

still extremely fast: ~300 Hz rate
(RGB-D camera has 30 Hz 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

video



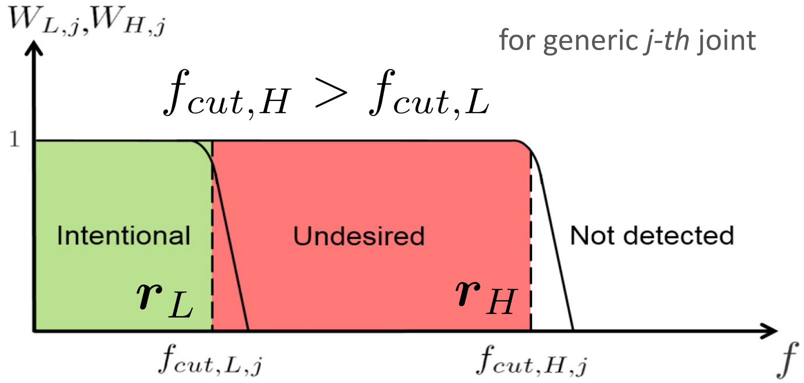
Collision or collaboration?

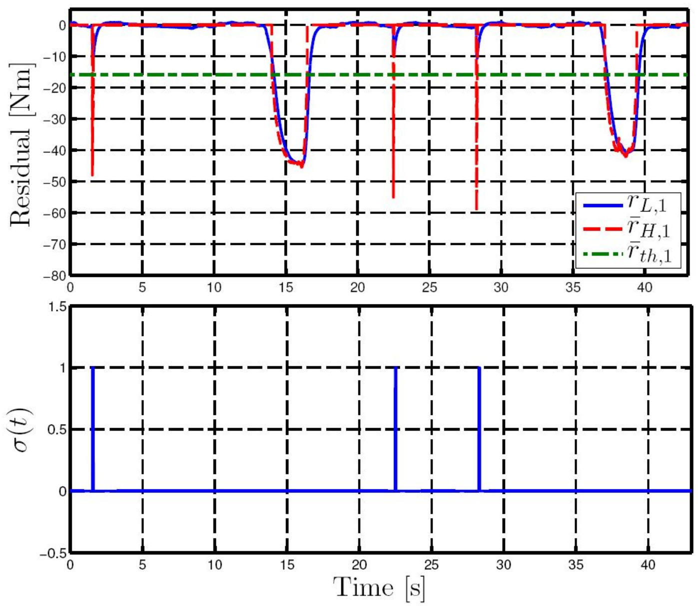
Distinguishing hard/accidental collisions and soft/intentional contacts

- 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 free robot motion



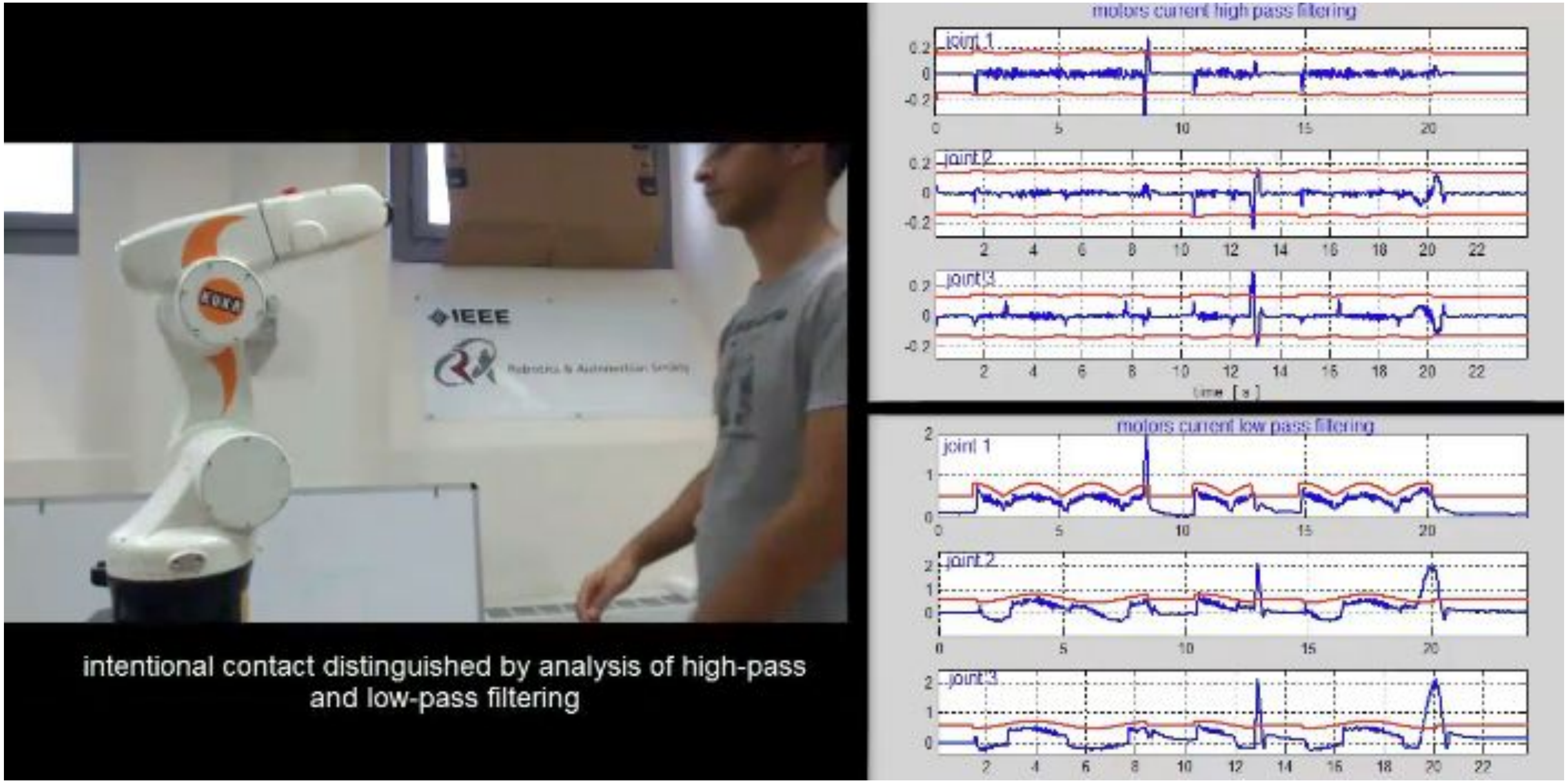


video

Distinguish hard and soft contacts ("poor man" version)

Hard = accidental collision ⇔ Soft = intentional contact for collaboration (ICRA 2013)

video



using both high-pass and low-pass filtering of motor currents
— here manual guidance is chosen as collaboration mode

Trials with human subjects

A. Collision detection & B. Distinguishing a soft from a hard contact (October 2013)

26 volunteers (informed students, in the age range 20-24, about 20% female)

A. a total of **168 collisions**, in series of 5 for each user (with repeated attempts)

collision detection	trial 1	trial 2	trial 3	trial 4	trial 5	total count	% over all trials	% over all attempts	% over last trials
at attempt # 1	19	19	18	23	25	**104**	80%	61.9%	92.6%
at attempt # 2	6	2	4	3	1	**16**	12.3%	9.5%	3.7%
at attempt # 3	1	4	3	0	0	**8**	6.2%	4.8%	0%
at attempt # 4	0	1	1	0	0	**2**	1.5%	1.2%	0%
# of user trials	26	26	26	26	26	**130**	**100%**	**-**	**-**
robot fails to stop	8	13	13	3	1	**38**	-	22.6%	3.7%
# of user attempts	34	39	39	29	27	**168**	-	**100%**	**100%**
false stops						**6**	4.6%	3.6%	

B. 416 contacts, **half** of which were intended to be **soft**

distinguishing between soft contacts (S) and accidental collisions (H)	number of soft trials	number of successes	number of fails	% of successes	% of fails
group 1: sequence SSHHSSHH	52	39	13	75.0%	25.0%
group 1: sequence HHSSHHSS	52	44	8	84.6%	15.4%
group 2: sequence SSSSHHHH	52	44	8	84.6%	15.4%
group 2: sequence HHHHSSSS	52	45	7	86.5%	13.5%
overall	**208**	**172**	**36**	**82.7%**	**17.3%**

→ end-users experience a “learning” process

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 at the contact
  - 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

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

Contact force estimation

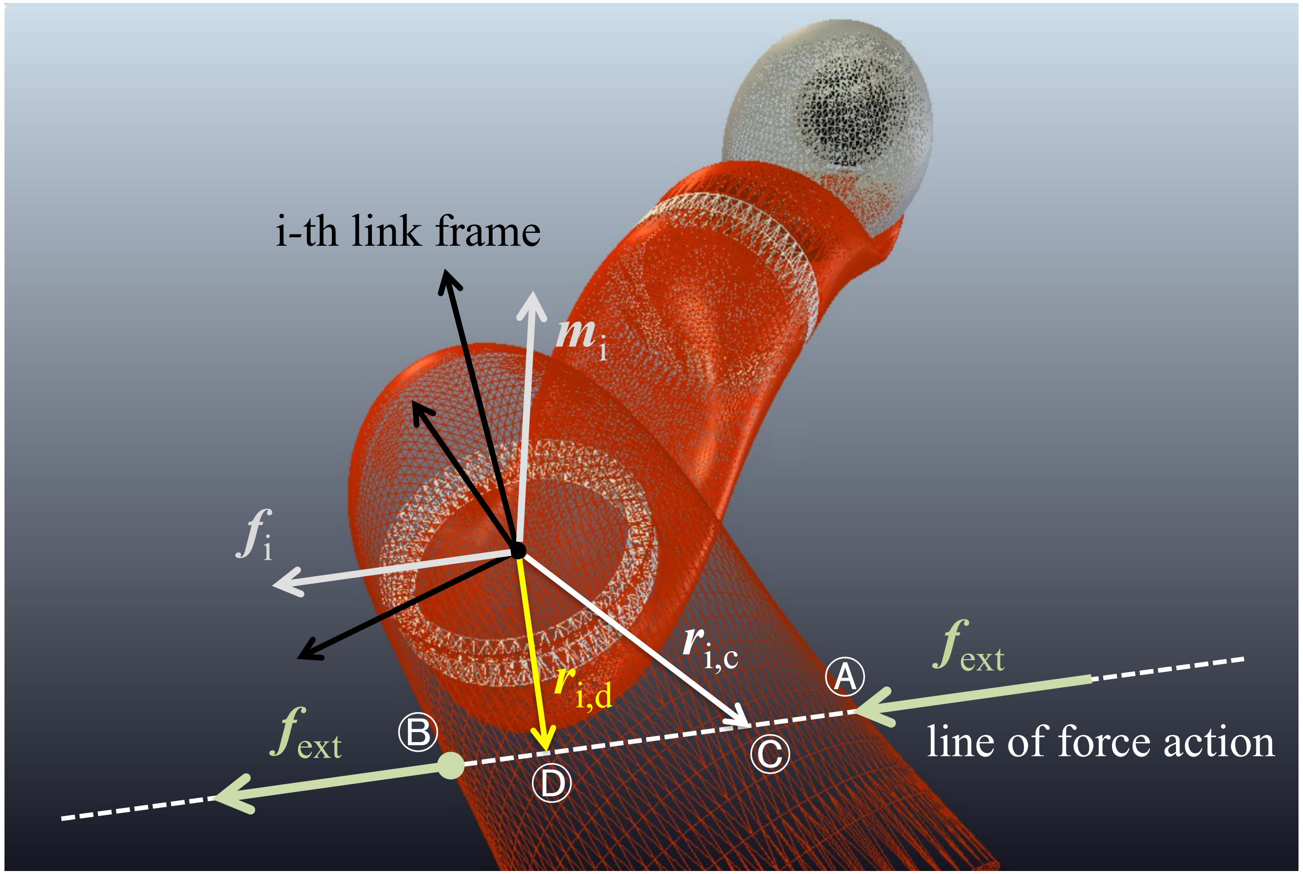
Used within an admittance control scheme (IROS 2014)

video

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 ...



Collaboration control

How to use the estimate of an external contact force (e.g., on KUKA LWR4+)

- 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
    - an **admittance** control law (in **velocity FRI** mode)
    - an **impedance** or **force** control laws (needs **torque FRI** mode)

  all implemented **at contact level**

- e.g., admittance control law using estimated contact force
  - 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

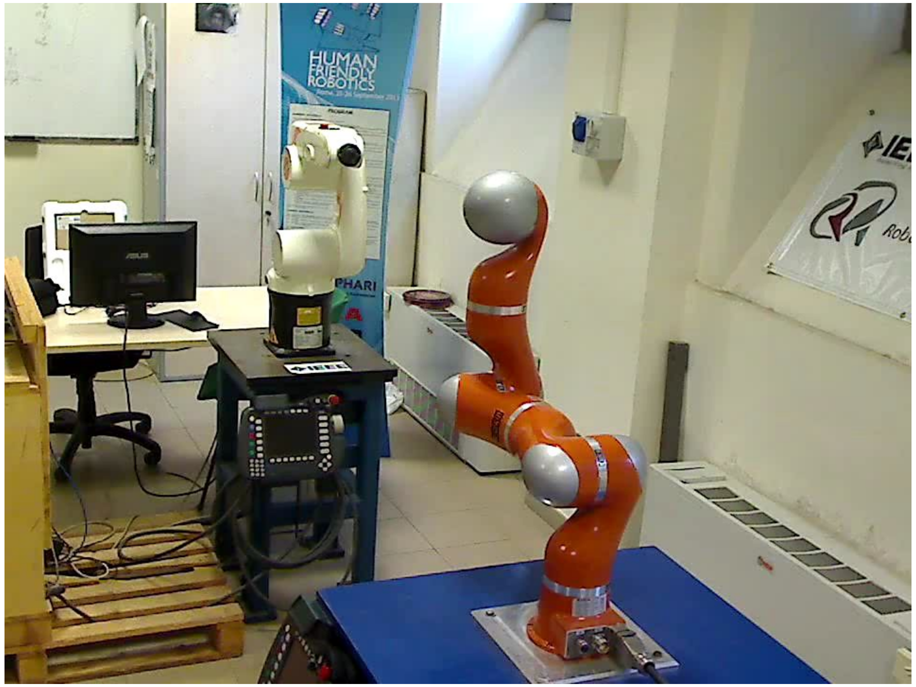
Control of generalized impedance

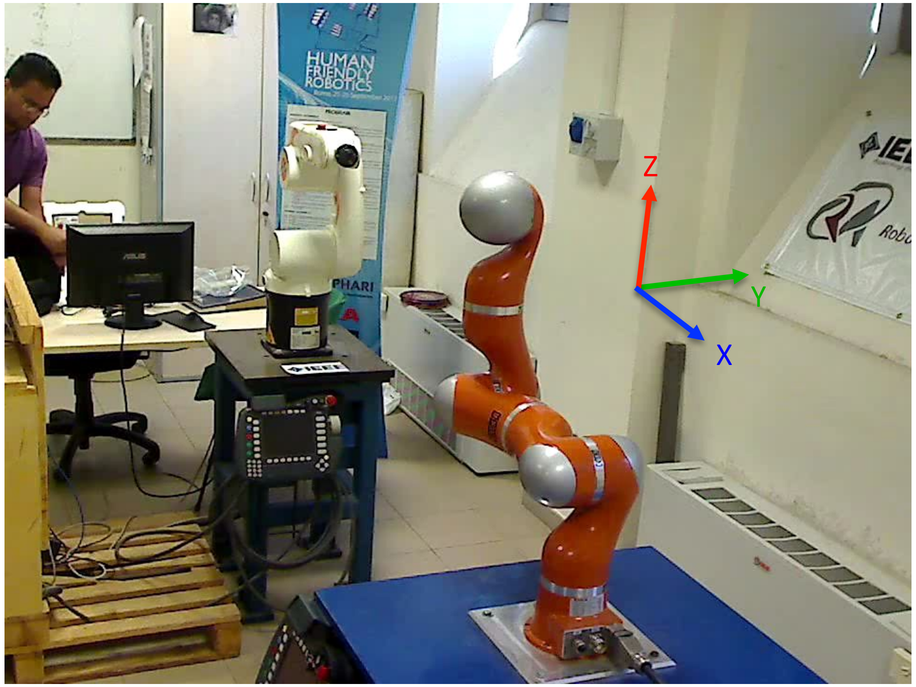
pHRC at the contact level (ICRA 2015)

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





videos

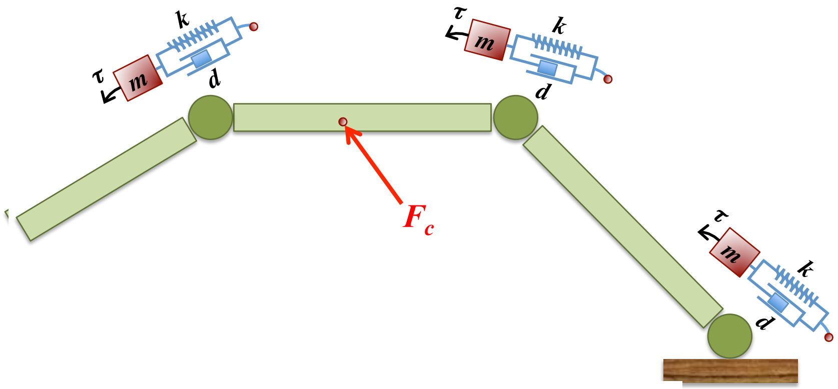
contact force **estimates** are used here **only** to detect and localize contact in order to start a collaboration phase

contact force **estimates** used **explicitly** in control law to modify robot inertia at the contact (M_{dX} = 20, M_{dY} = 3, M_{dZ} = 10 [kg])

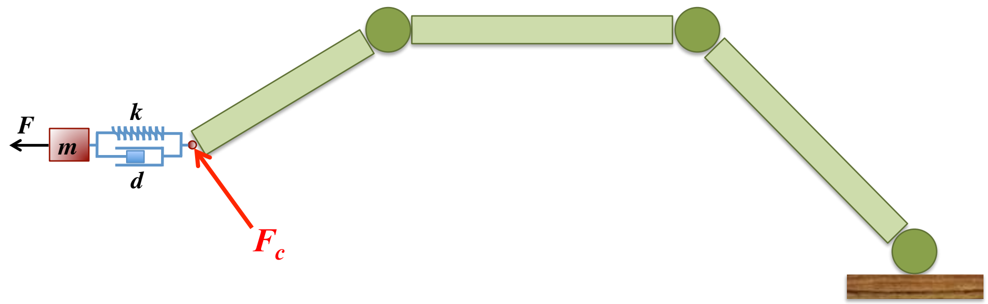
Impedance-based control of interaction

Reaction to contact forces by generalized impedance —at different levels

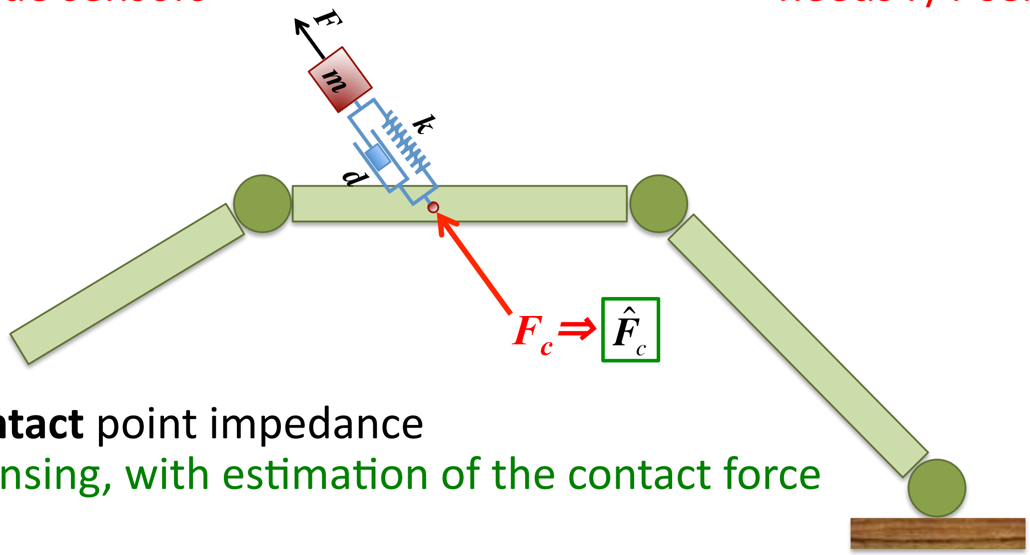
consider a fully rigid robot



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

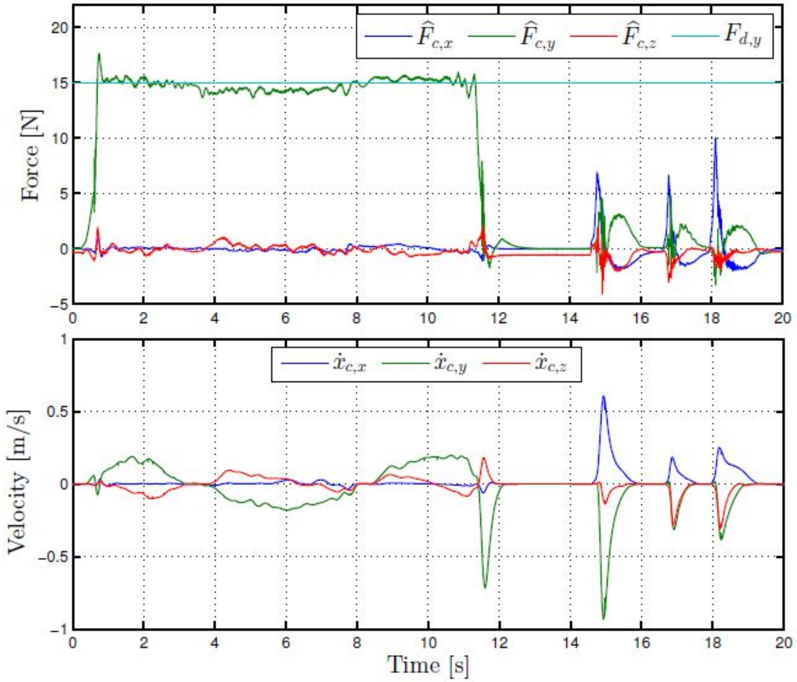
Control of generalized contact force

Direct force scheme

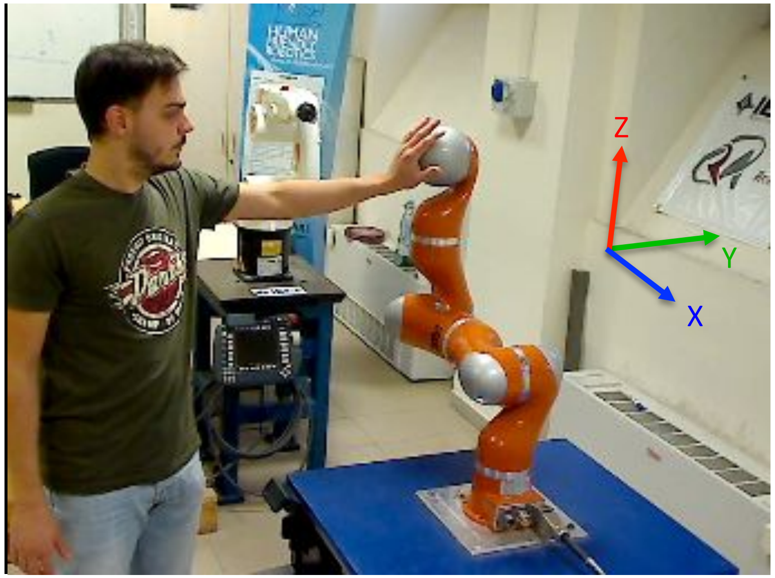
- explicit **regulation** of the **contact force** to a desired value, by imposing

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

- 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

drift effects in poor control of contact force

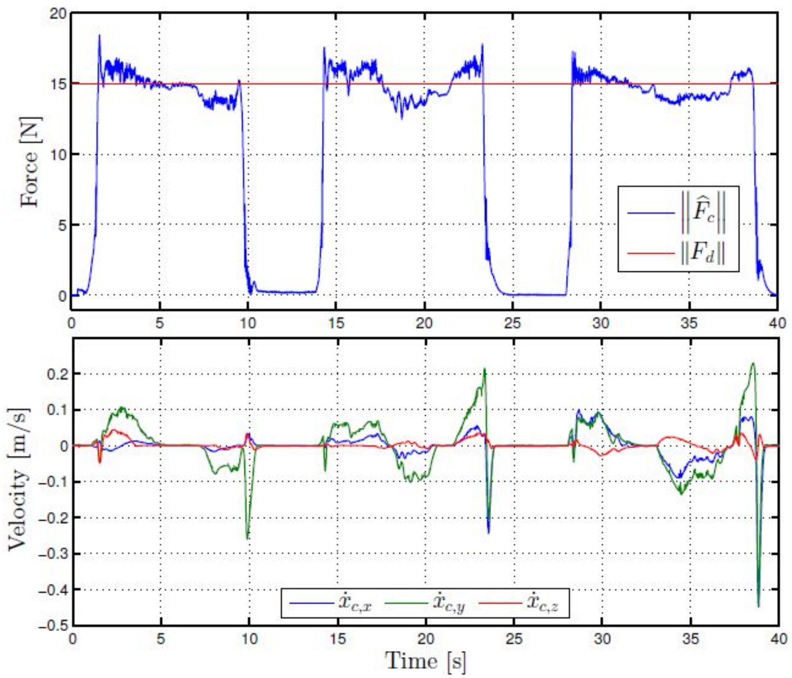
Control of generalized contact force

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

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

- force control law is able to regulate exactly contact forces under static conditions



task-compatible control of contact force

- 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)
  - collision avoidance based on depth space data
  - distinguishing intentional/soft contacts from accidental/hard collisions
  - estimation of contact force and location, by combining inner/outer sensing
  - whole-body admittance/impedance/force control laws, generalized at the contact level

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Take home messages

A list of Q&A (1/2)

- Need robot dynamic model and/or joint torque sensing for collision detection?
  No
- Are lightweight/torque-controlled robots needed for collision avoidance?
  Definitely no!!
- Why not to rely on additional sensing as long as feasible?
- Do Kinect-based systems for pHRC monitoring comply with safety standards?
  No (or not yet)
- What do we require for more advanced robot reaction (other than just stop)?
  Collision isolation capabilities in the controller
- Is redundancy with respect to the task useful for collision avoidance or reaction?
  Yes, absolutely
- How fast should a certified controller be in stopping the robot?
  100 ms may not be enough...

Take home messages

A list of Q&A (2/2)

- Can we smoothly transit from collision avoidance to a HRC robot behavior?
  We need probably to stop first
- Is a model of the human behavior/intention needed for monitoring pHRC?
  Possibly, but not for tracking distances to some human body parts
- How can we reliably distinguish intentional contacts from accidental collisions?
  Multi-modal interaction helps indeed (voice, gestures, other than just forces)
- Is it possible for robots in motion to perform collaborative tasks with humans?
  Yes, but at present we typically violate the safety standards!
- For which tasks is controlling the exchanged contact force relevant?
  E.g., if the robot needs to push hard against something, hold firmly a work-piece
- Can contact force estimation at a generic point of the robot be "sensorless"?
  Under special conditions, yes (e.g., for dynamic payload estimation). Otherwise, with F/T sensor (at e-e or at the base) or without, using RGB-D or without, ..,
- Localizing the contact point (with human or environment) is good for whole-body manipulation...