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A Control Architecture for Human-Robot Collaboration

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Human-friendly robotics

The domain of **physical** and cognitive HRI

traditional robotics

replacing humans

co-workers on factory floor

human-friendly robotics

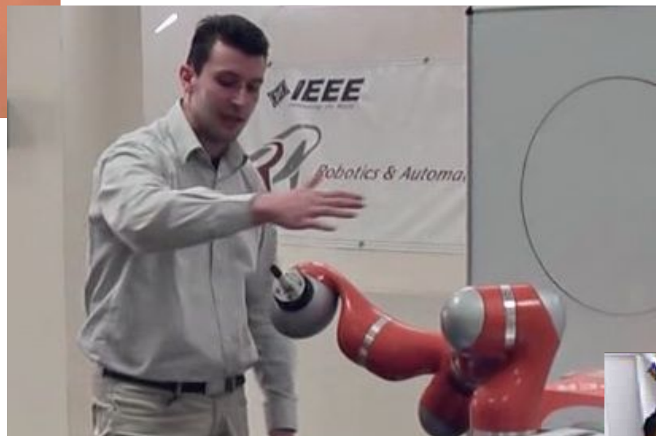
collaborating with humans

personal robots in service

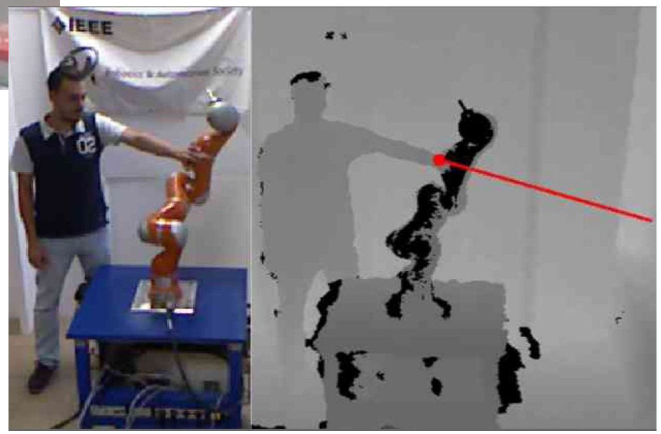
Collision and contact handling

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)

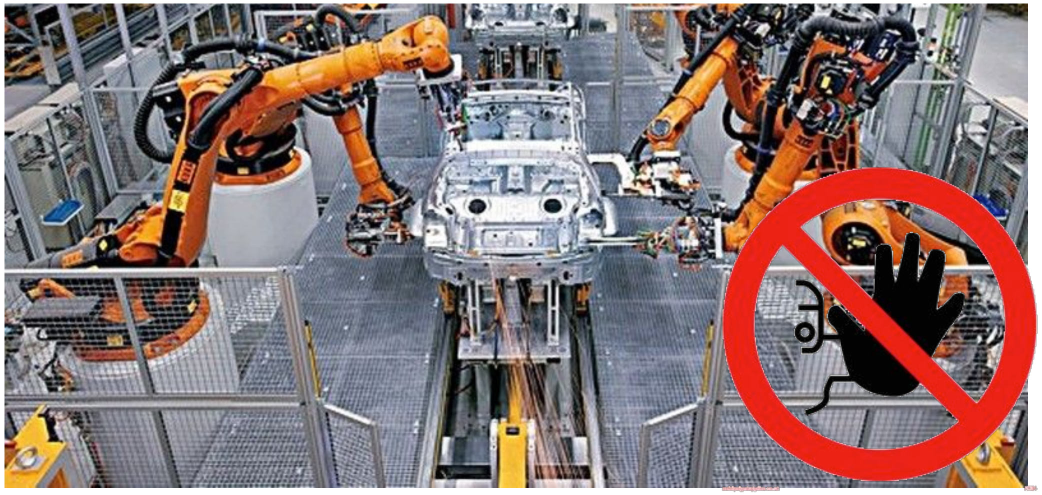


estimation and control
of intentional forces
exchanged at the contact
(**without** force or touch sensors)

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, stop/slow down robot motion in presence of humans [**ISO 10218**]) are not appropriate for collaborative pHRI



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

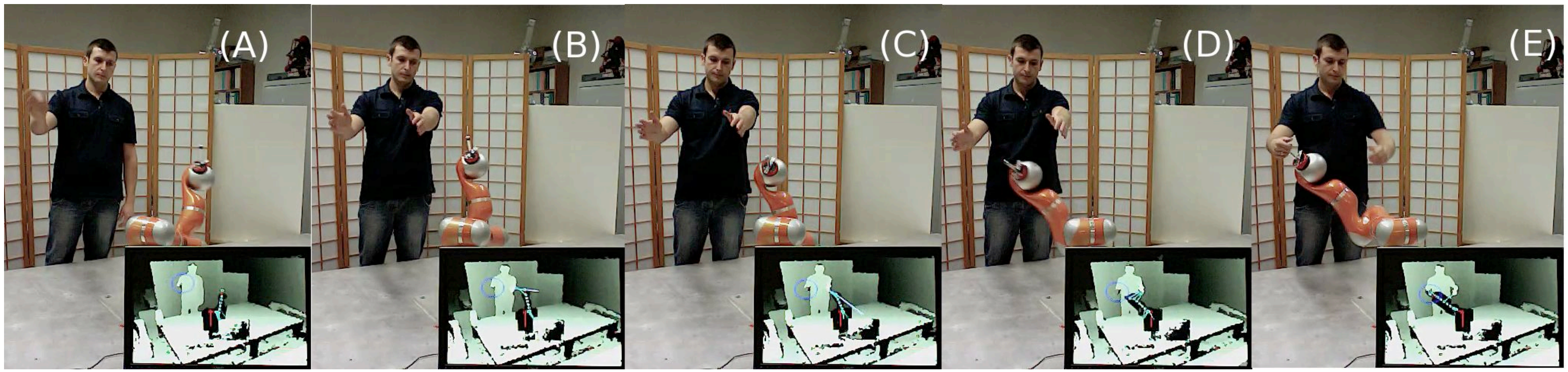
safe HR coexistence

Physical HRI

Hierarchy of consistent behaviors (BioRob 2012)

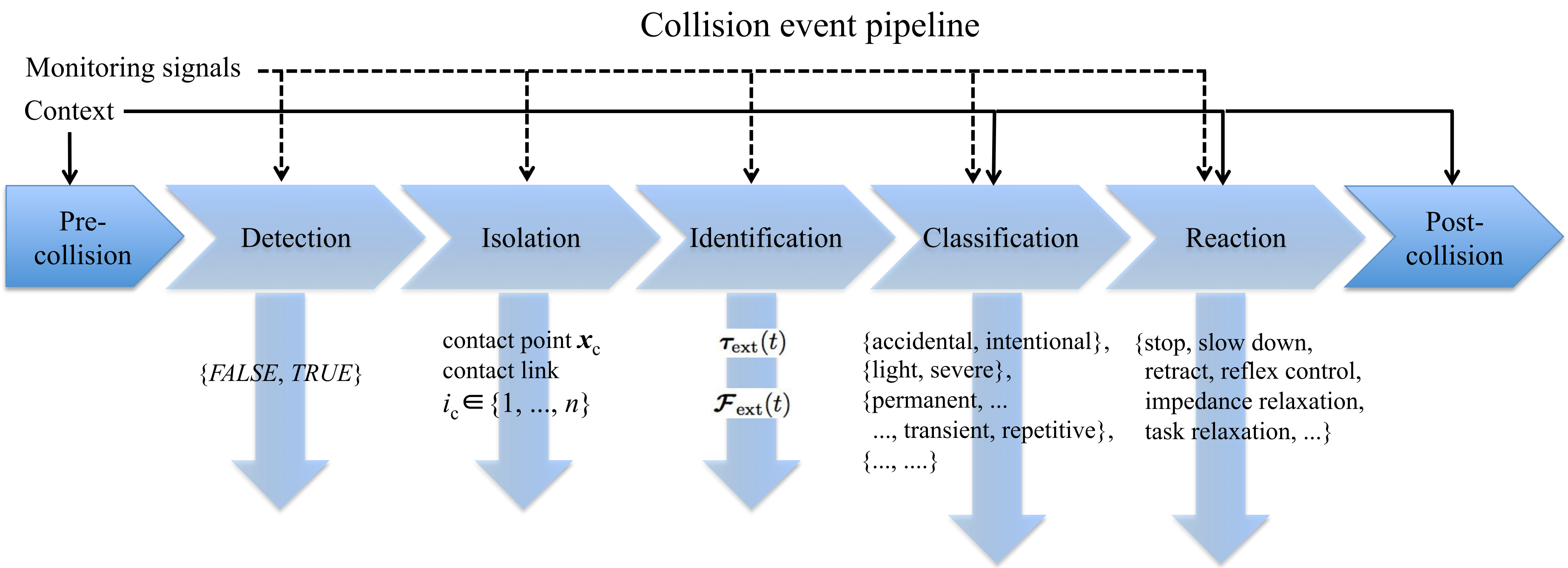
Collaboration occurs when the robot performs complex tasks with direct human interaction and coordination

Two modalities which are not mutually exclusive: contactless and physical



Collision event pipeline

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

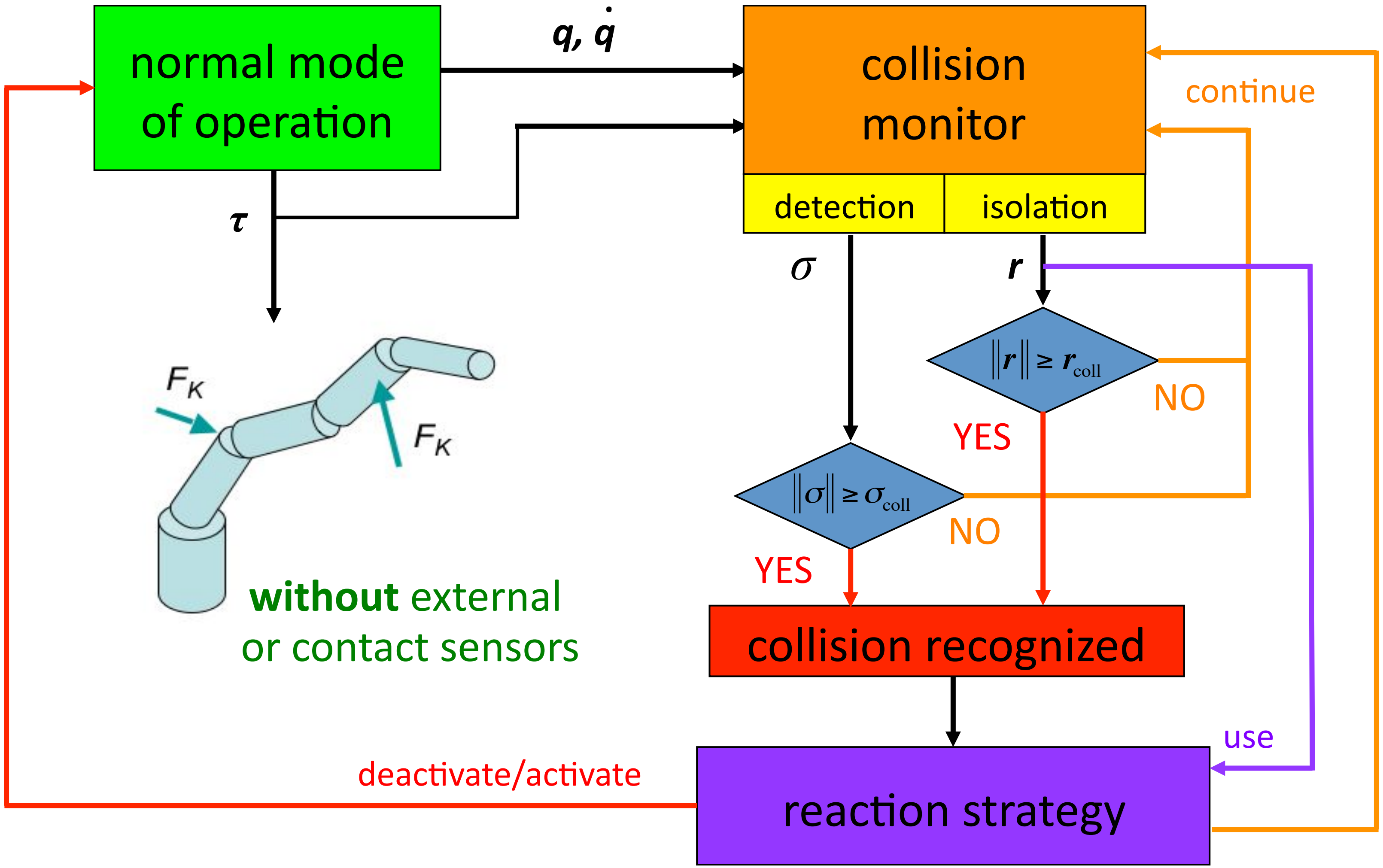


Monitoring signals can be generated from sensors or models (signal- or model-based methods)

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

Monitoring robot collisions

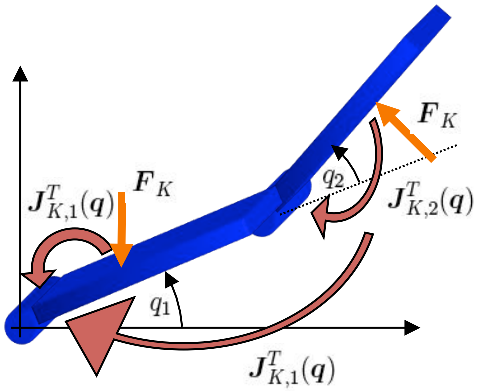
Applies equally to **rigid and elastic** joints, **with and without** joint torque sensing



Collision detection and isolation

Based on **residuals** for robots with rigid or **elastic joints** (ICRA 2005)

- dynamic model of robots with elastic joints and environment interaction



$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau_J + \tau_K$$

joint torque due to link collision

$$\tau_K = J_K^T(q) F_K$$

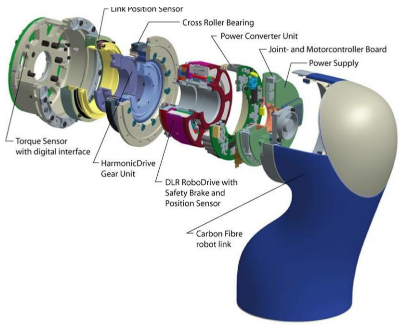
$$B\ddot{\theta} + \tau_J = \tau$$

motor torques commands

elastic torques at the joints

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

- DLR LWR-III robot with multiple joint sensors
  - **encoders** for motor (θ) and link (q) positions
  - joint **torque sensor** for τ_J



monitoring signal:
(link) momentum-based residual vector

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

$K_I > 0$ (diagonal and large)

$$\dot{r} = -K_I r + K_I \tau_K$$

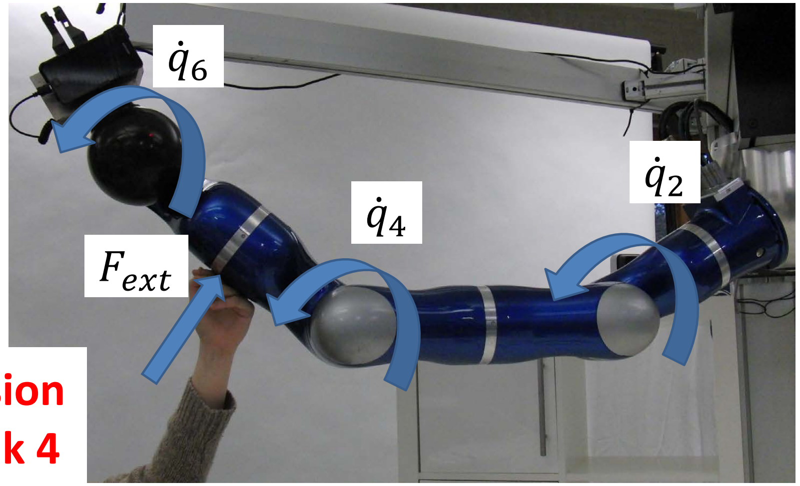
$r \approx \tau_K$ **detection** (over a threshold)

$$r = [\, * \quad \dots \quad * \quad * \quad \underset{i+1}{0} \quad \underset{\dots}{\dots} \quad \underset{N}{0} \,]^T$$

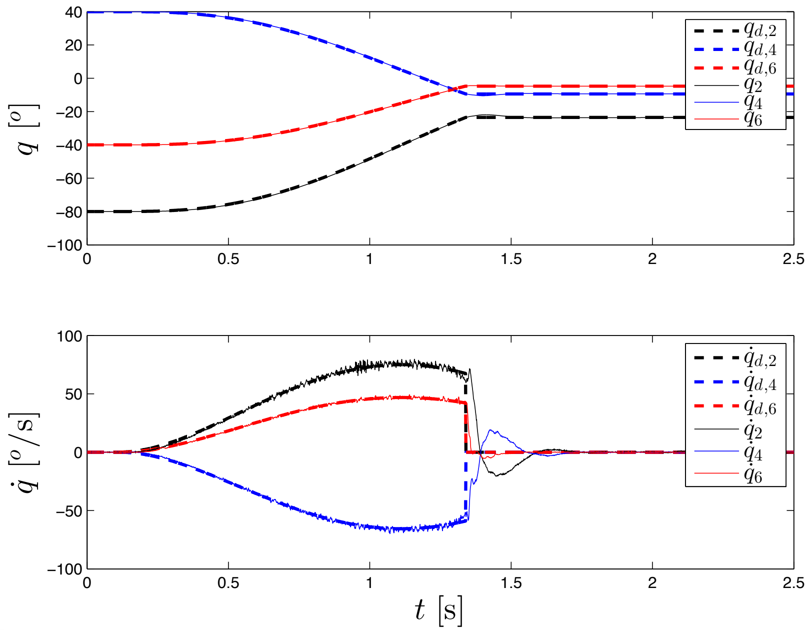
isolation (collision at link i)

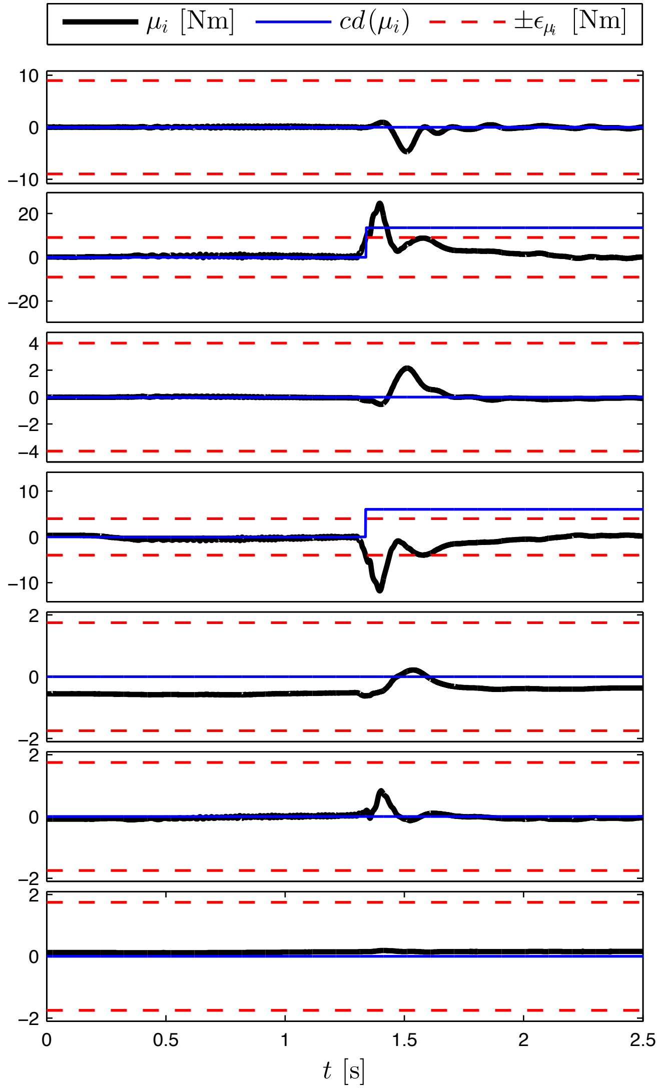
Momentum-based method

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



collision at link 4



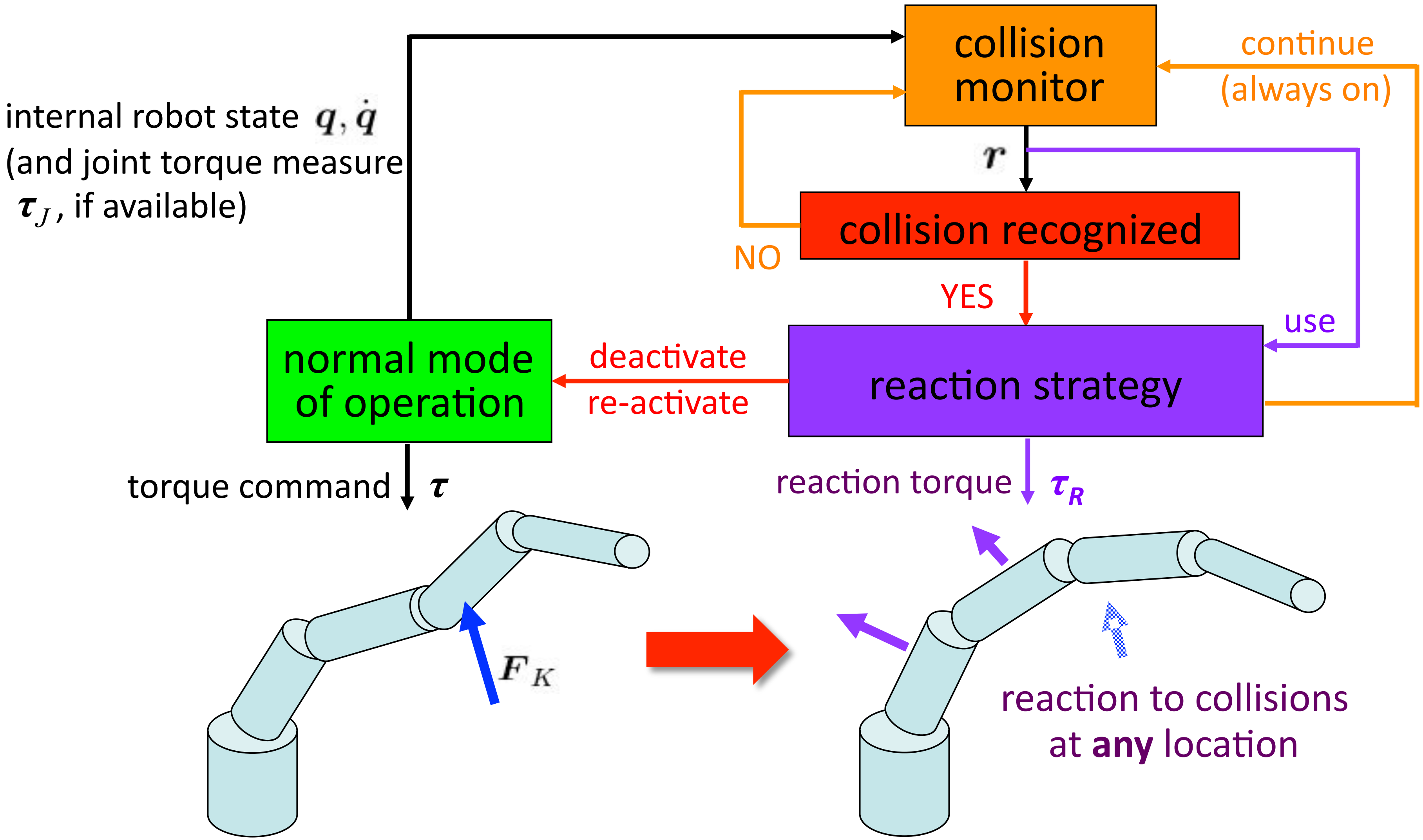


cd_2 = ON

cd_4 = ON

Collision reaction

Using the residuals



Collision detection and reaction

Residual-based experiments on DLR LWR-III (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

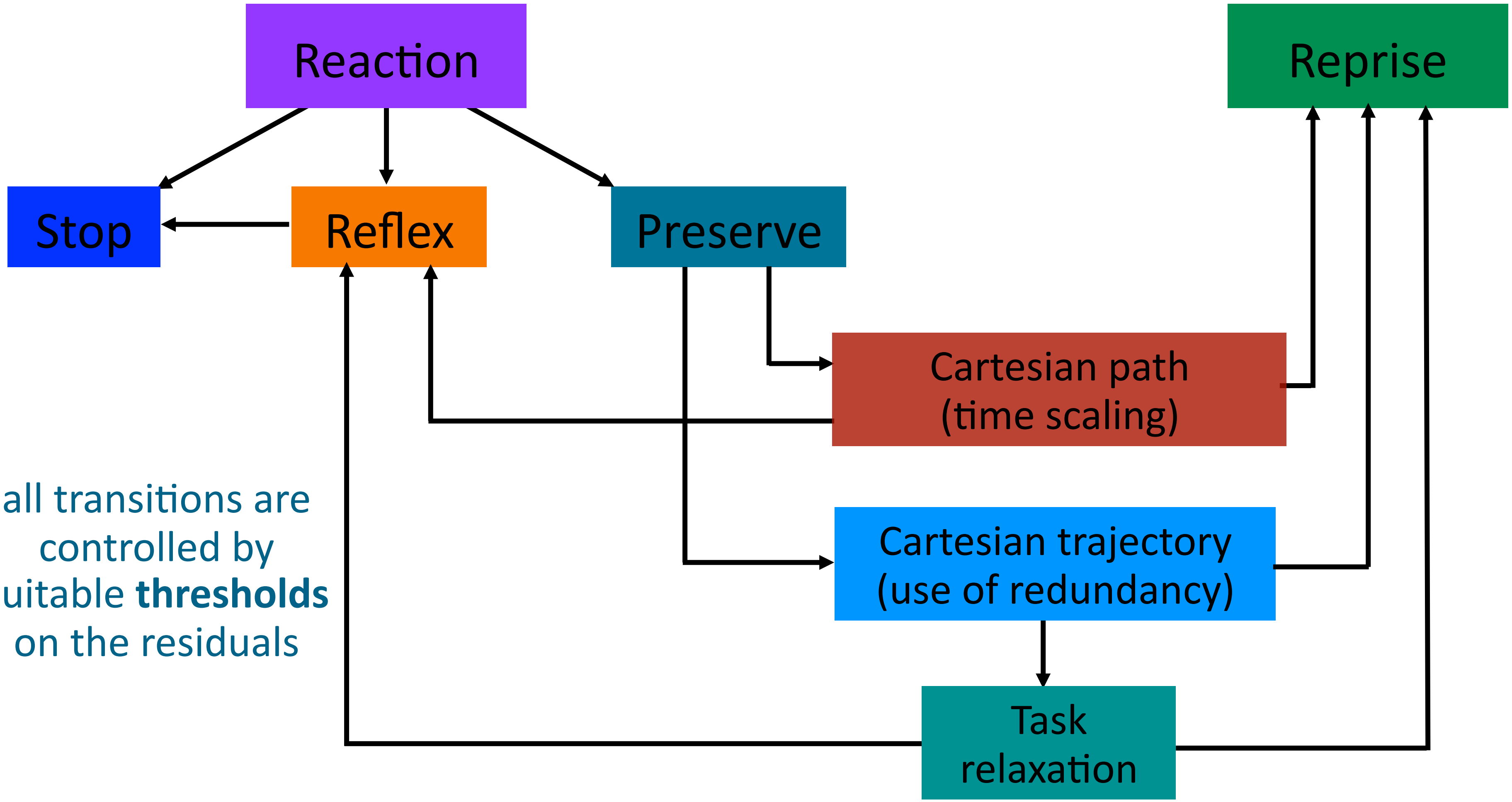
videos

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

Collision reaction

Portfolio of possible robot reactions

residual amplitude ∝ severity level of collision



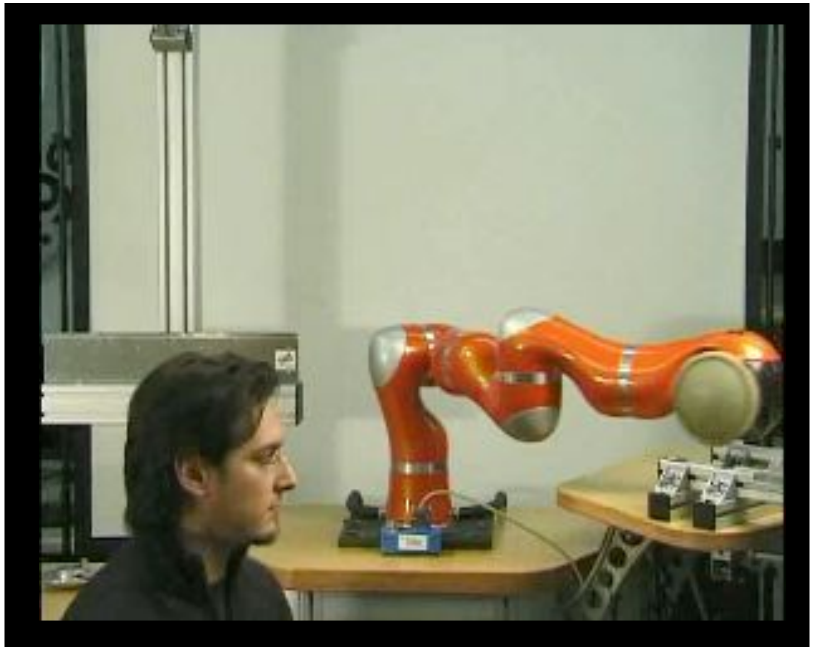
all transitions are controlled by suitable **thresholds** on the residuals

Collision reaction

Further examples (IROS 2008)

- without external sensing
- any place, any time ...

video



- "volunteer" (now, Prof.) Sami Haddadin!

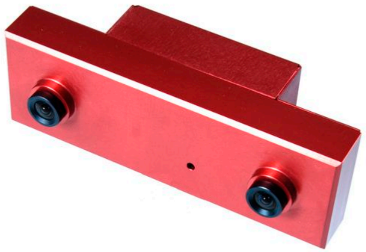
video

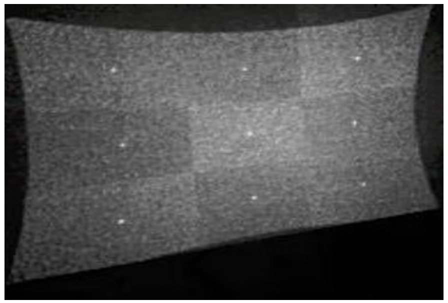
- robot is position-controlled on a geometric path
- timing slows down, stops, possibly reverses

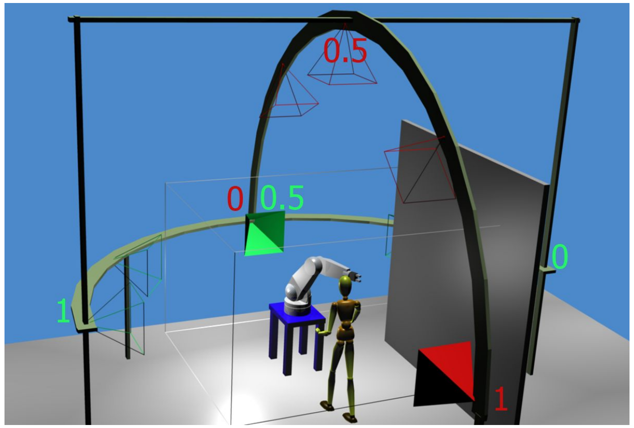
Collision avoidance

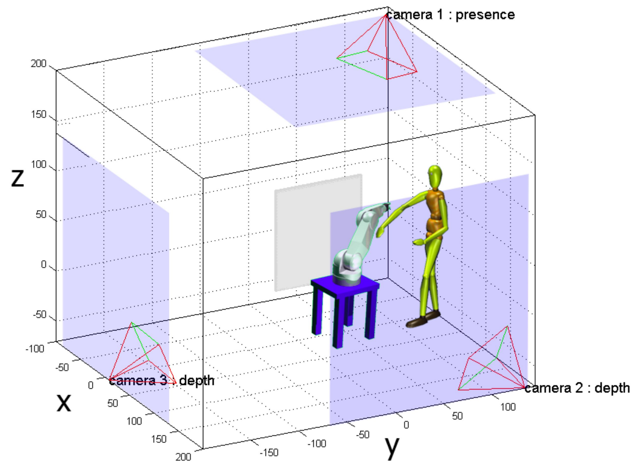
Using exteroceptive sensors to monitor robot workspace (ICRA 2010)

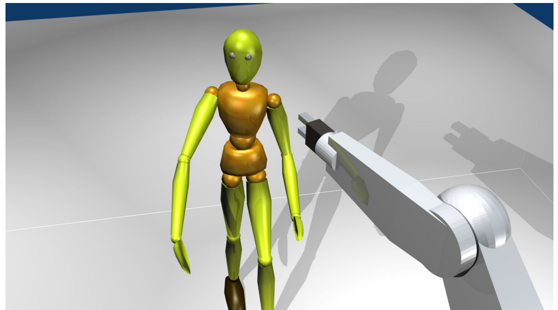
- **external sensing:** stereo-camera, TOF, structured light, **RGB-Depth**, laser, presence, ... placed optimally to minimize occlusions (robot is to be removed from images)

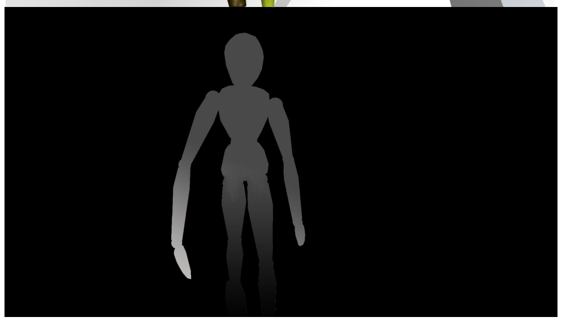






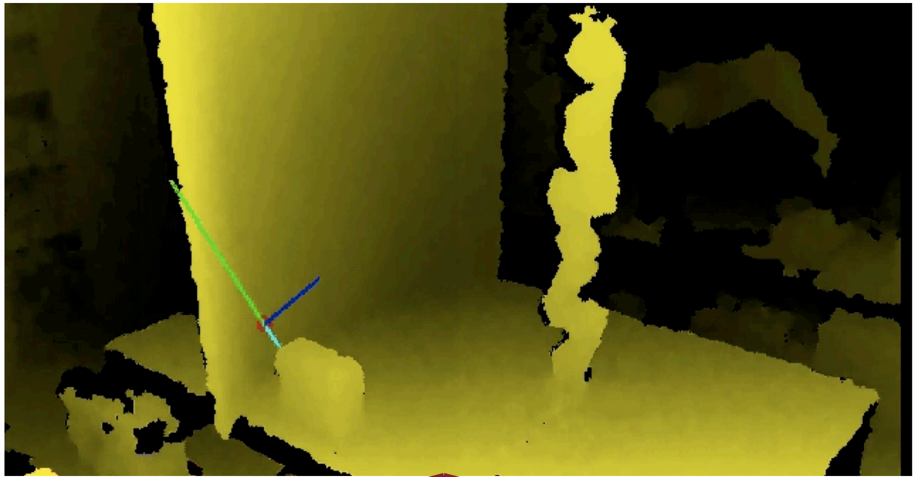






Depth image

How to use it?



Configuration Space

Cartesian Space

Depth Space

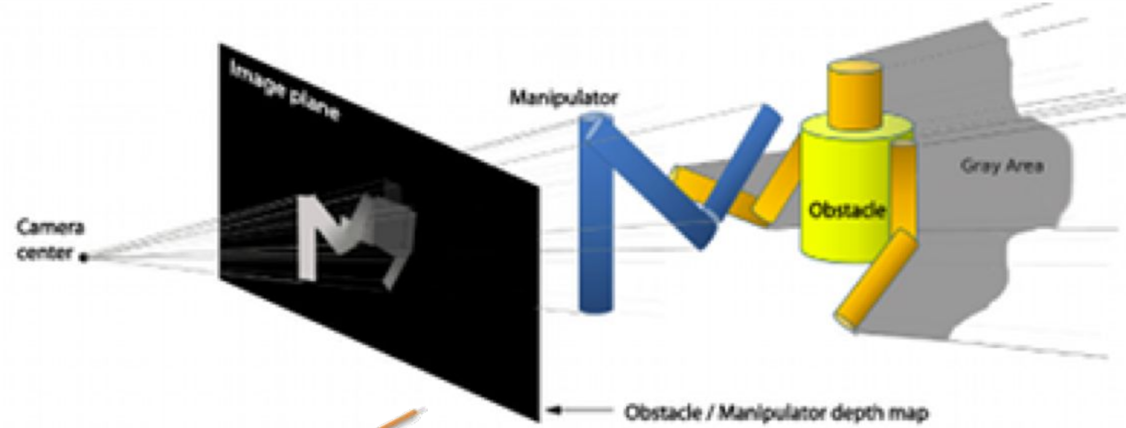
Depth space

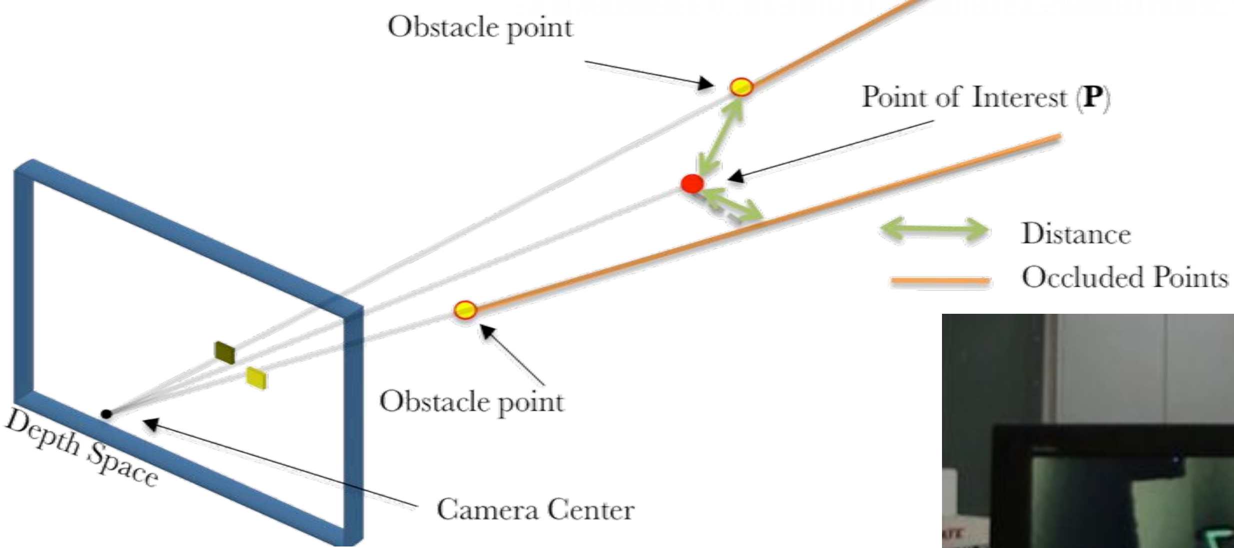
2 ½ space for efficient robot-obstacle distance computations (ICRA 2012)

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

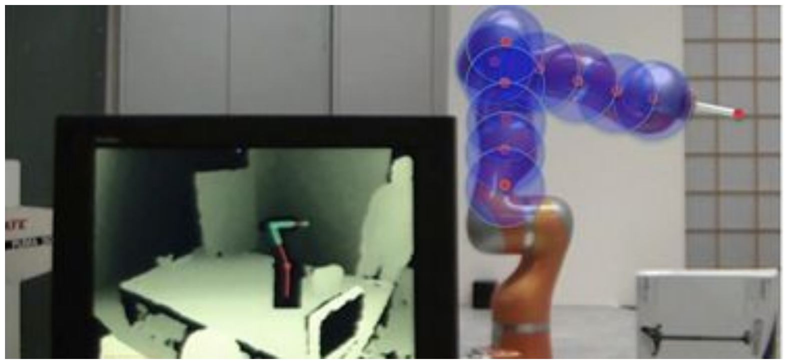
$$p_y = \frac{y_C f s_y}{z_C} + c_y$$

$$d_p = z_C$$



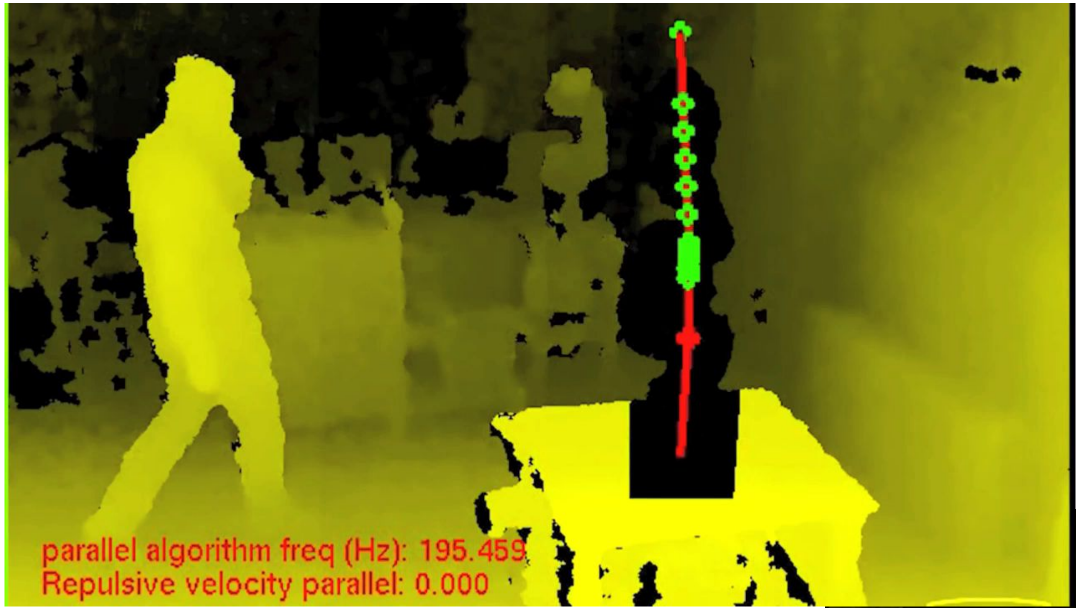


using then, e.g.,
artificial potentials
for **collision avoidance**



Safe physical human-robot collaboration

Extracts from long video at IROS 2013



coexistence through collision avoidance

video

video

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

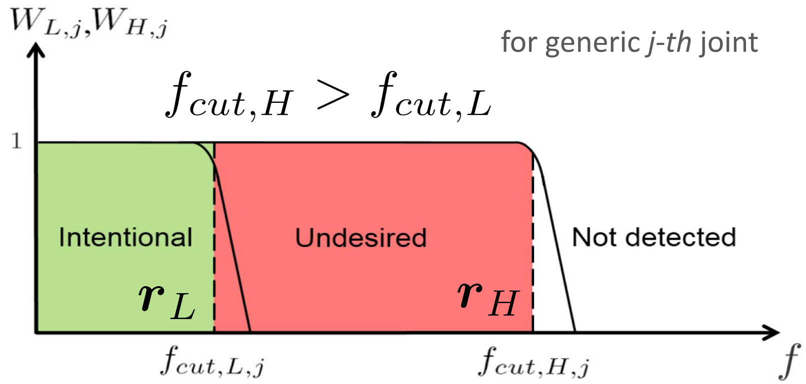
Collision or collaboration?

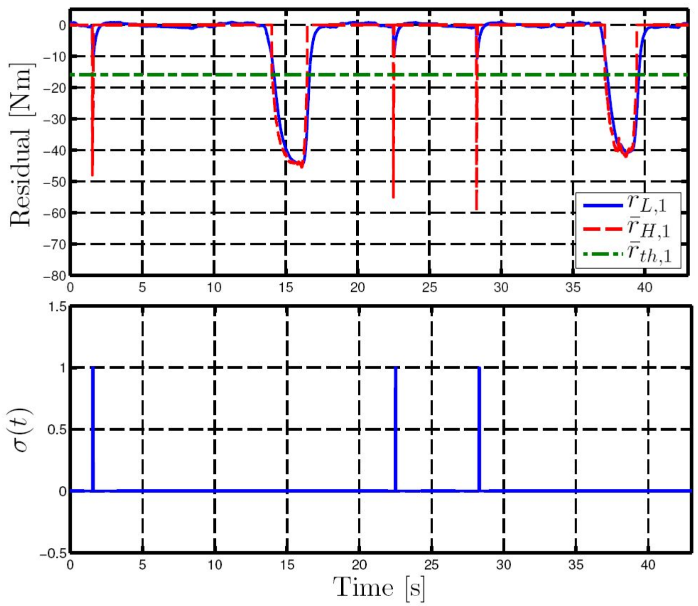
Distinguishing hard/accidental collisions and soft/intentional contacts

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

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

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





video

Force estimation for collaboration

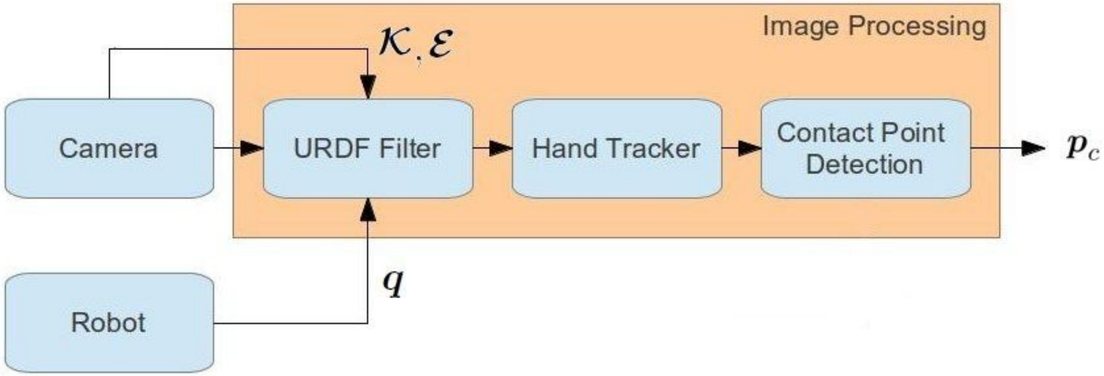
Combining internal and external sensing

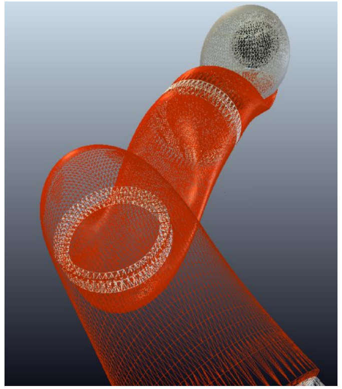
- Task
  - localize (in the least invasive way) points on robot surface where contacts occur
  - estimate exchanged **Cartesian** forces
  - control the robot to react to these forces according to a desired behavior
- Solution idea
  - use residual method to **detect** physical contact, **isolate** the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

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

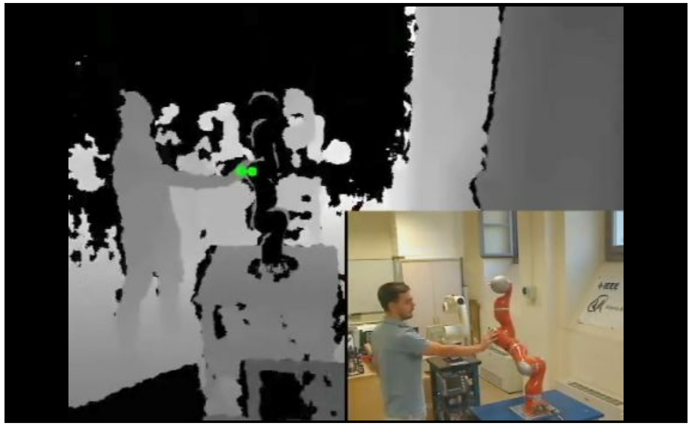
Distance and contact estimation

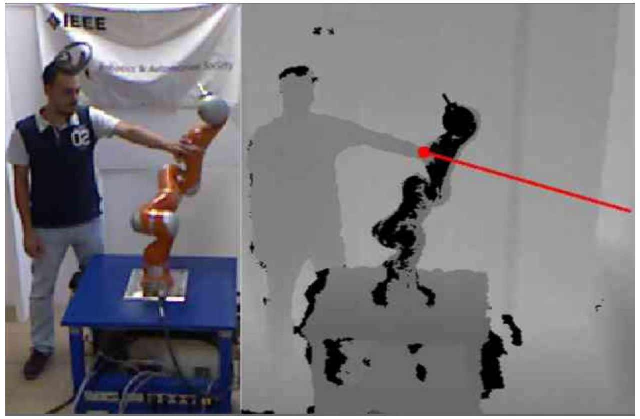
Using Kinect, CAD model, distance computation, and residual to localize contact





- 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 is applied in parallel to both left and right hand (or other body parts)





Validation of the "virtual" force sensor

Experiments with KUKA LWR 4

- Evaluation of estimated contact force

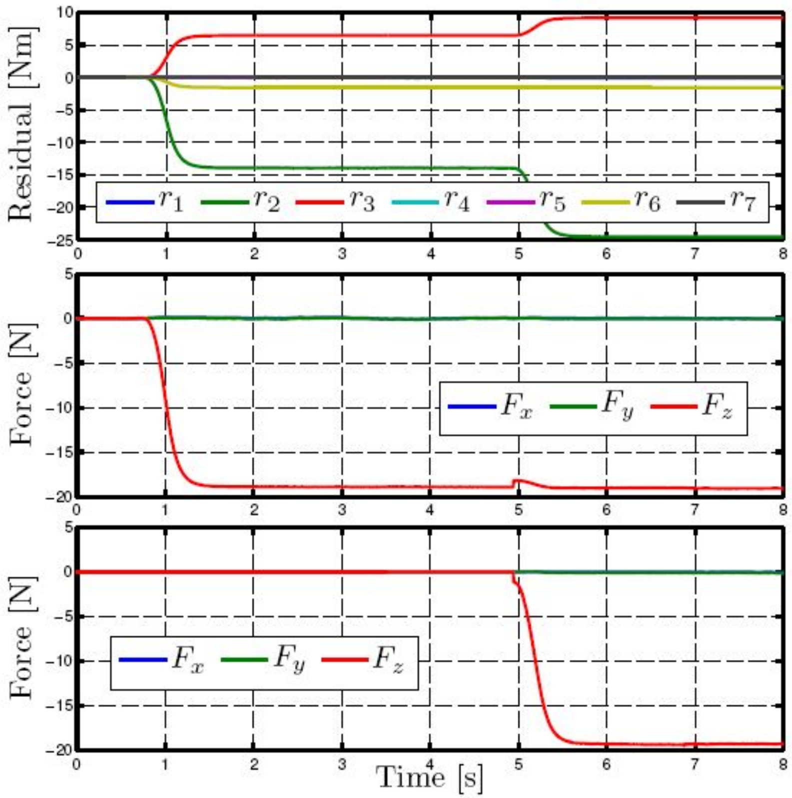
$$\widehat{\boldsymbol{F}}_c = \left(\boldsymbol{J}_c^T(\boldsymbol{q})\right)^{\#} \boldsymbol{r}$$

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

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

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

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



case of two masses

Contact force estimation

Used within an admittance control scheme (IROS 2014)

video

Collaboration control

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

- shaping the robot dynamic behavior in specific collaborative tasks
  - joint carrying of a load, holding a part in place, whole arm **force** manipulation, ...
  - robot motion controlled by
    - 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

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

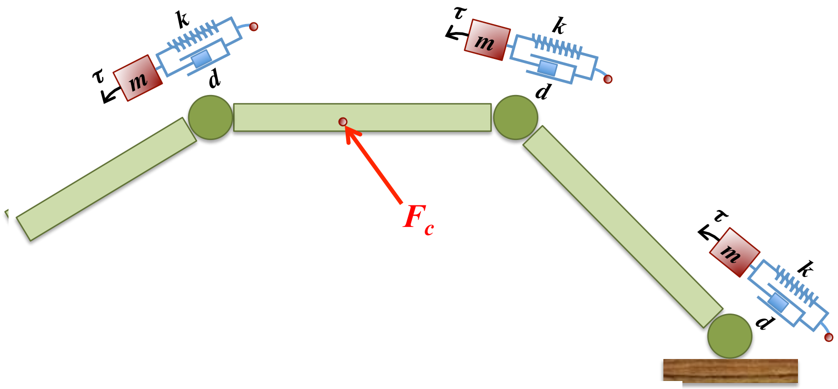
$$\boldsymbol{F}_a = \widehat{\boldsymbol{F}}_c + \boldsymbol{K}_p(\boldsymbol{p}_d - \boldsymbol{p}_c), \qquad \boldsymbol{K}_p = k_p \boldsymbol{I} > 0$$

↖ initial contact point position when interaction begins

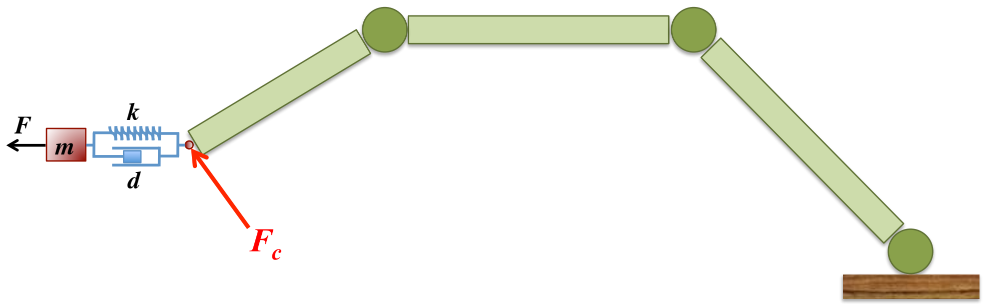
Impedance-based control of interaction

Reaction to contact forces by generalized impedance —at **different** levels

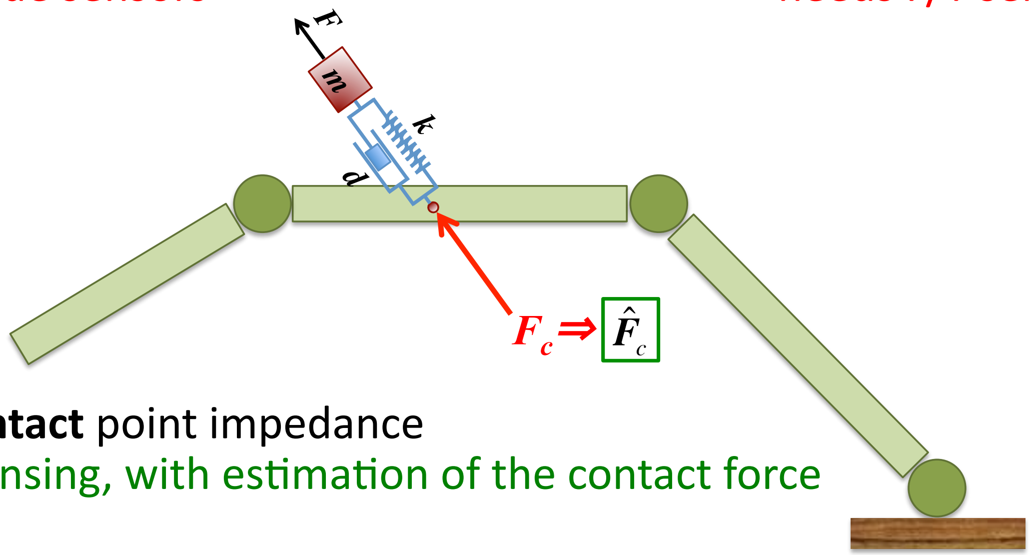
consider a fully rigid robot



Joint impedance
needs joint torque sensors



Cartesian impedance
needs F/T sensor



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

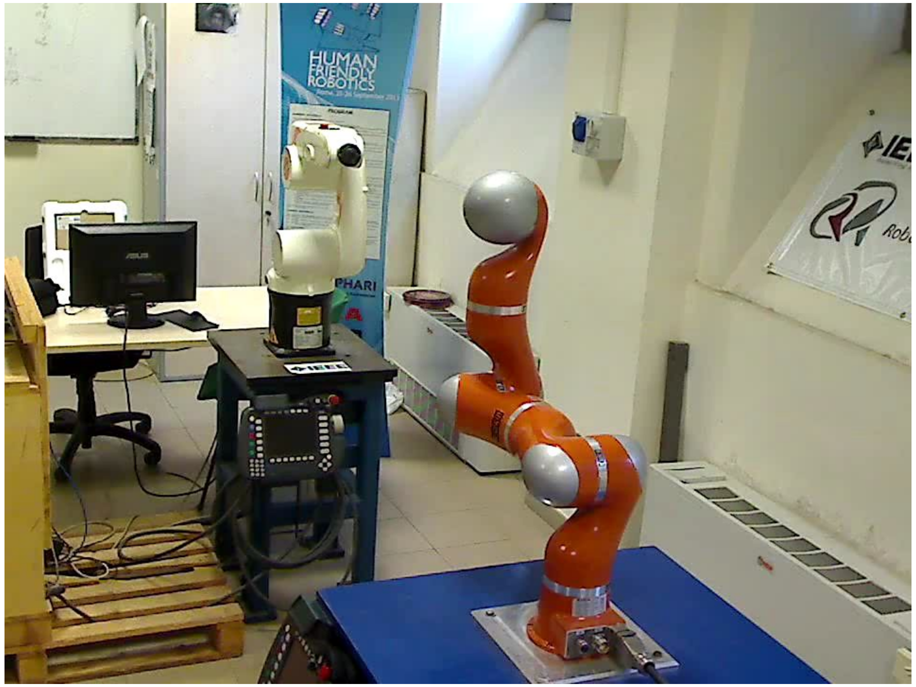
Control of generalized impedance

pHR collaboration at the contact level (ICRA 2015)

SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction

natural (unchanged) robot inertia at the contact

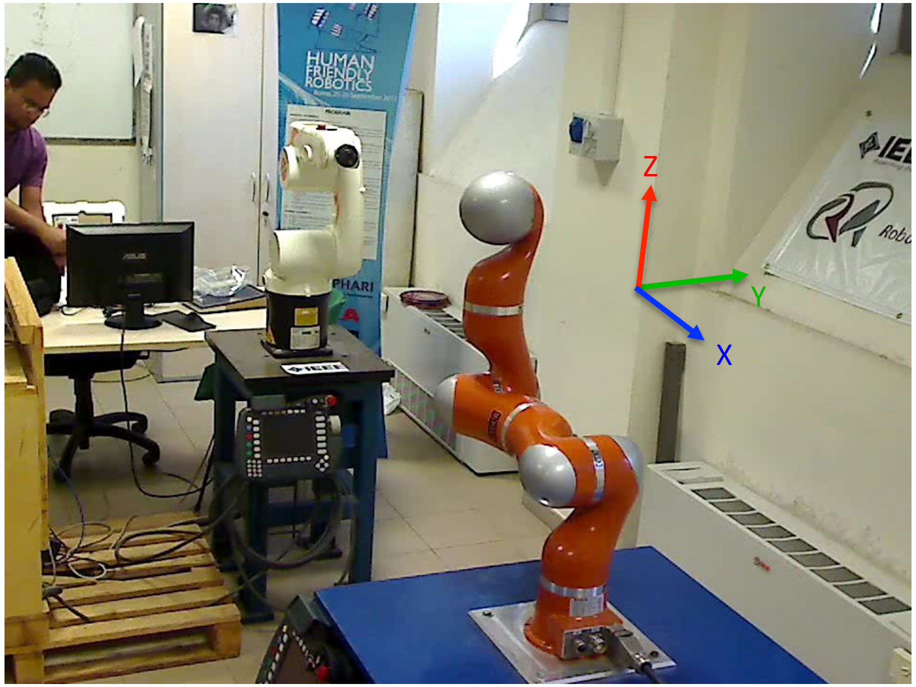
$$M_d = \left(J_c M^{-1} J_c^T\right)^{-1}$$



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

videos

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



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])

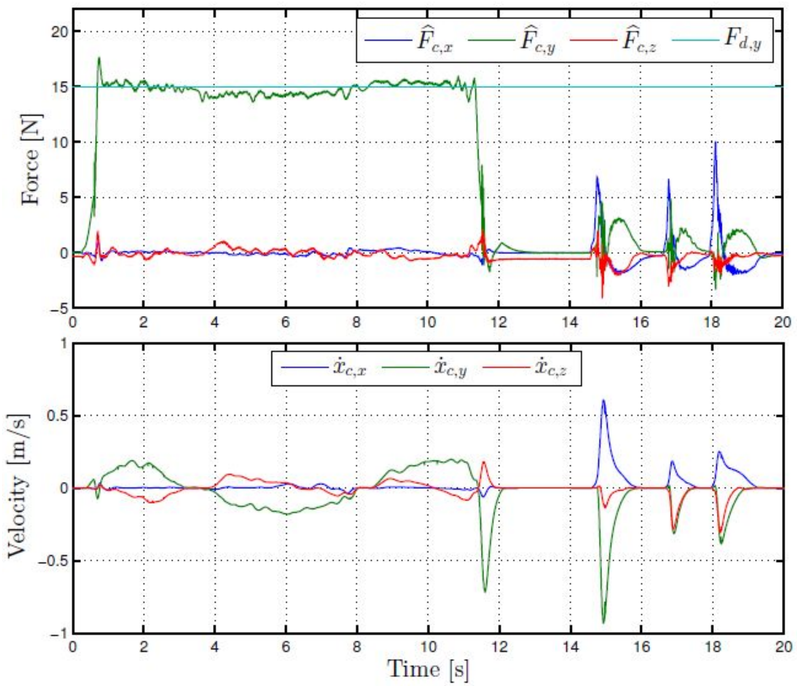
Control of generalized contact force

Direct force scheme

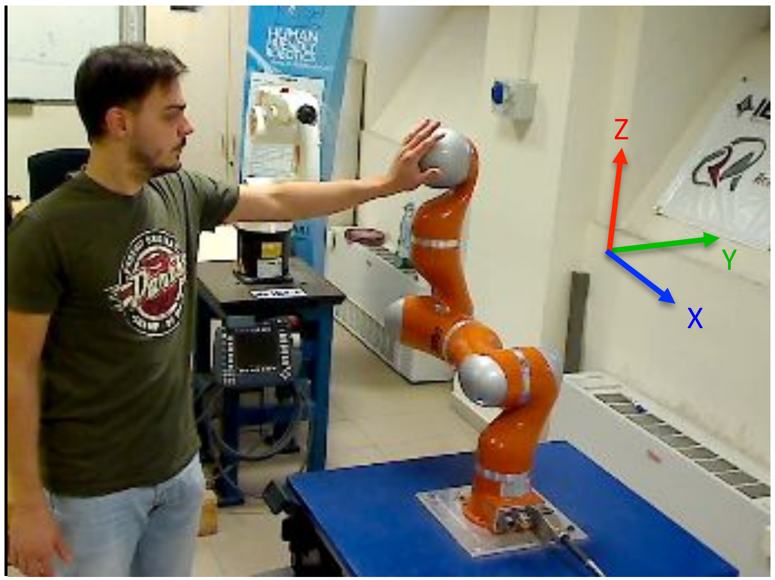
- explicit **regulation** of the contact force to a desired value, by imposing

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

- 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

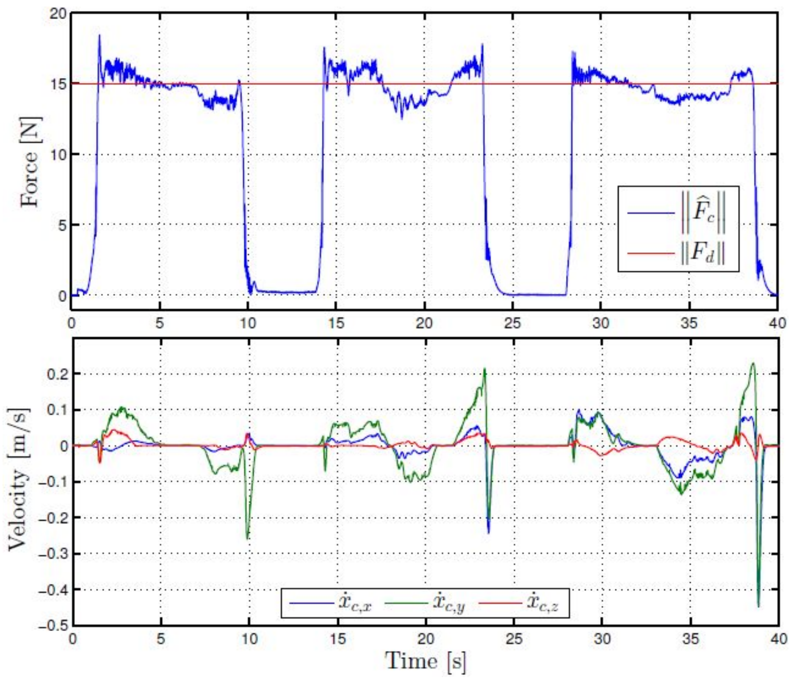
Control of generalized contact force

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

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

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



task-compatible control of contact force

Conclusion

Toward safer and efficient human-robot physical collaboration

- framework for safe human-robot coexistence and collaboration, based on hierarchy of consistent controlled behaviors of the robot
  - residual-based collision detection (and isolation)
  - portfolio of collision reaction algorithms (using also redundancy)
  - 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
  - admittance/impedance/force control laws, generalized at the contact level

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