Great Ideas in ICT 2014

Joint seminars of the PhD programs in:
Engineering in Computer Science; Automatica and Operations Research; Computer Science

Safe Control of Physical Human-Robot Interaction

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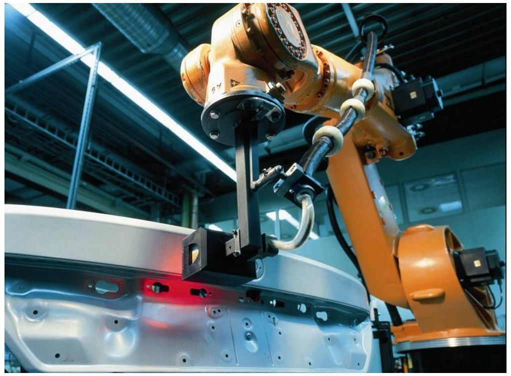
SAPIENZA
UNIVERSITÀ DI ROMA

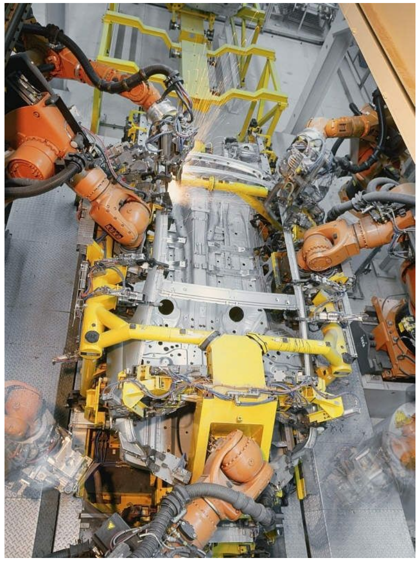
Robots in factories

The “cage”

Popular notions of robotics have long foreseen humans and robots existing **side-by-side** and **sharing work**



Until very recently, the reality has been quite different: industrial robots have been far **too dangerous** to share their workspace with humans



The traditional industrial perspective

Slowing down or stopping the robot when workspace can be accessed by a human

commercial video by ABB

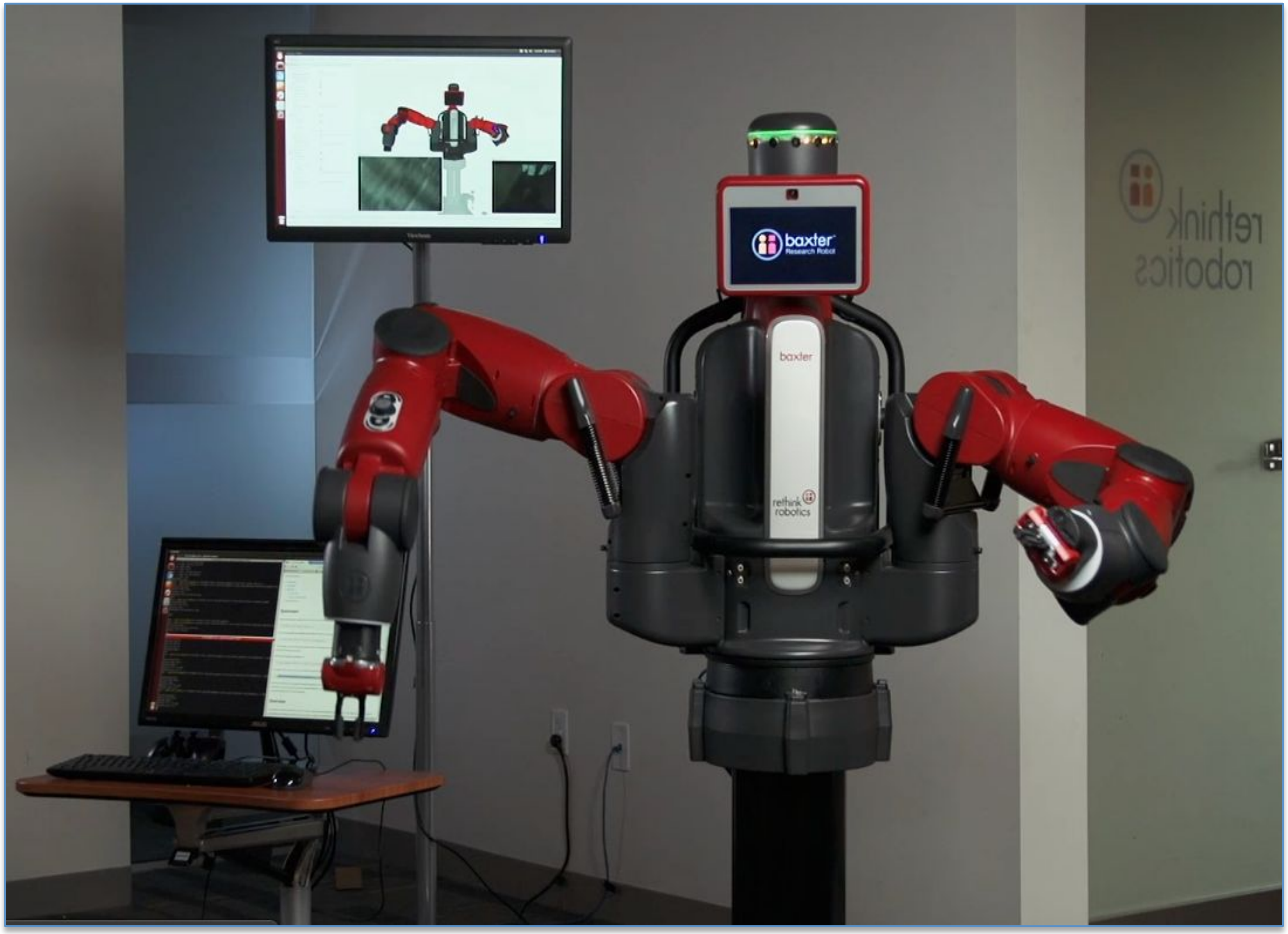
The innovative industrial perspective

Robot co-workers

video by SMERobot (EU project)

Bridging research and commercial products

Intuitive programming and multimodal HR communication



video of Baxter by rethink robotics (CTO Rodney Brooks)

Human-friendly robotics

The goal

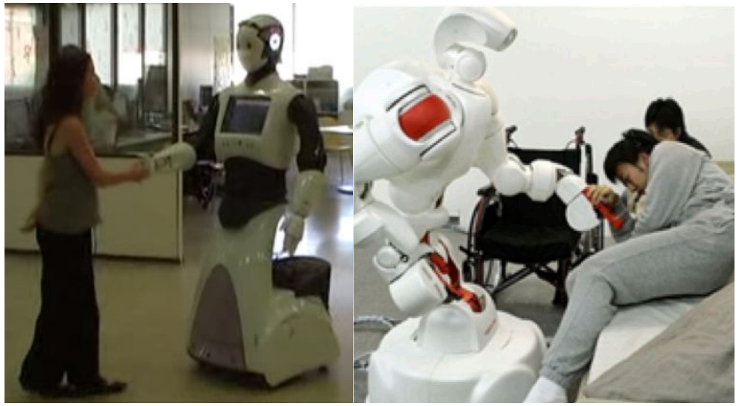
traditional robotics

replacing humans

co-workers on factory floor

human-friendly robotics

collaborating with humans



personal robots in service

Human-Robot Interaction

cognitive (cHRI) vs. physical (pHRI)

video

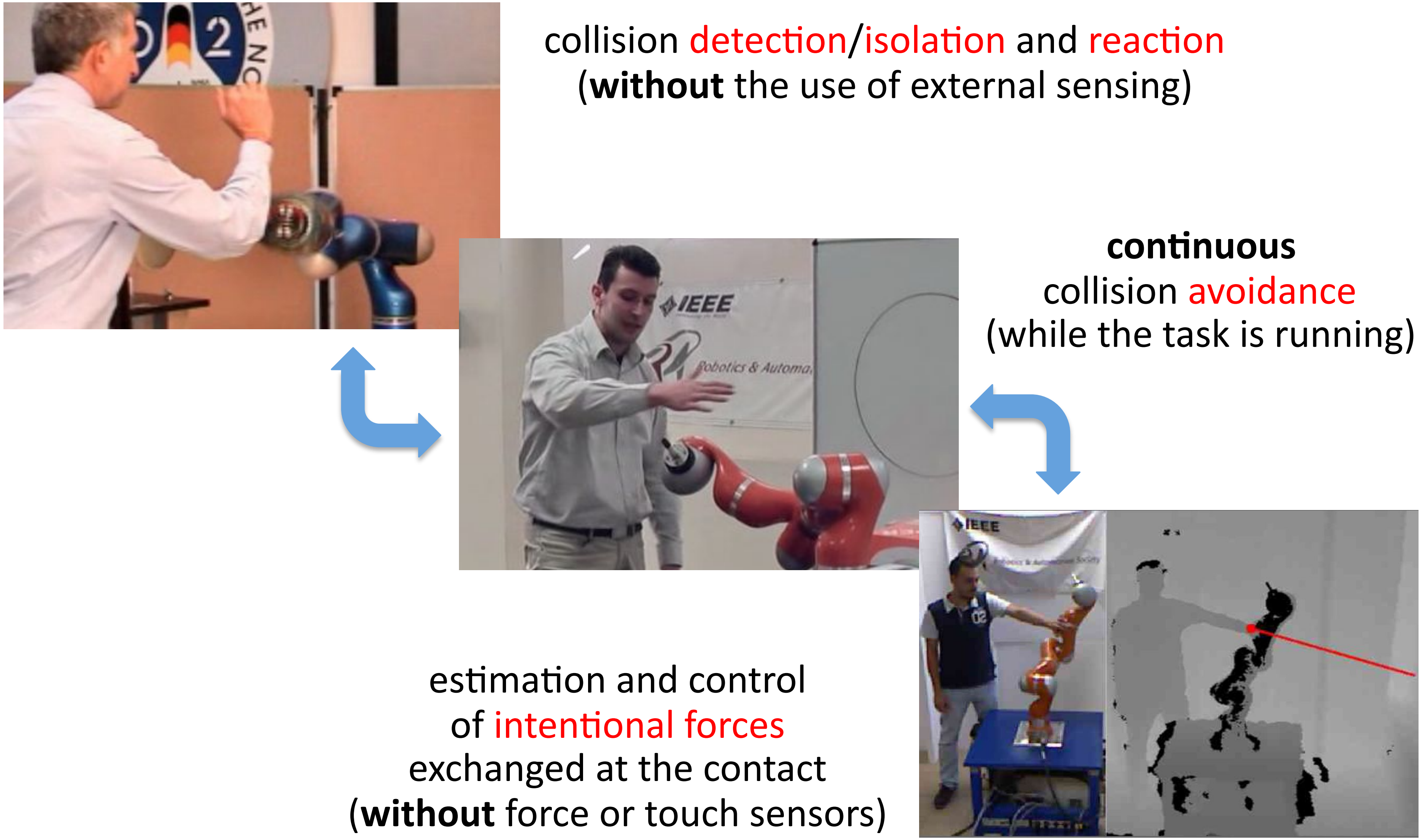
cognitive interaction:
Robot@CWE EU Project

video

physical interaction:
handshaking at PAL Robotics

Collision avoidance and contact handling

Basic safe 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)

What is SAPHARI about?

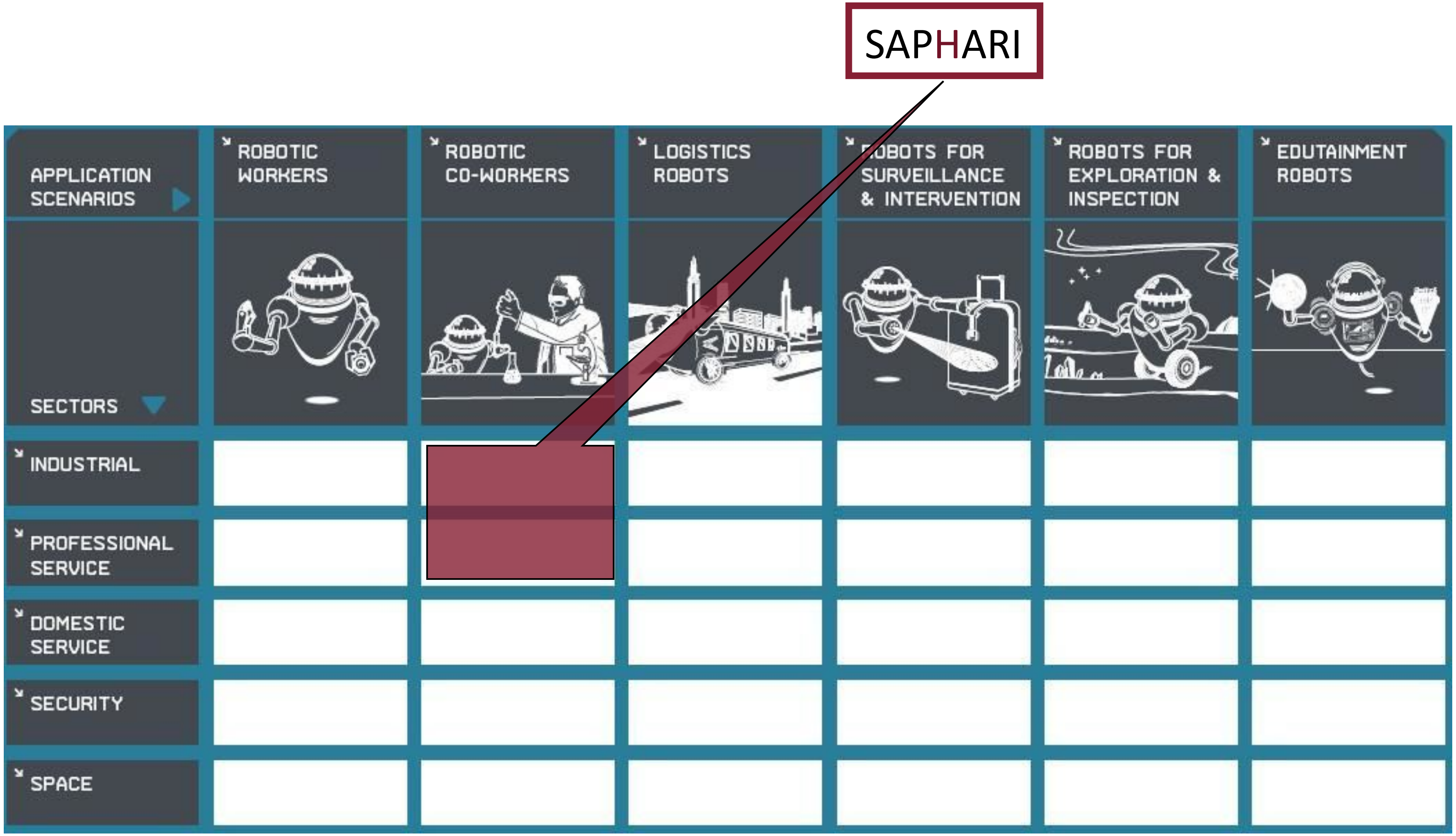
FP7 ICT European project (2011-15)

SAPHARI will bring to fruition co-workers in real world applications using the new technologies of ***soft robotics*** that combine ***cognitive reaction*** and ***safe physical human-robot interaction***

"Expanding and improving the functionalities of robotic systems and further developing relevant features, such as autonomy, ***safety***, ***robustness***, ***efficiency***, and ***ease of use***"

SAPHARI project classification

Challenge 2: Cognitive systems and robotics



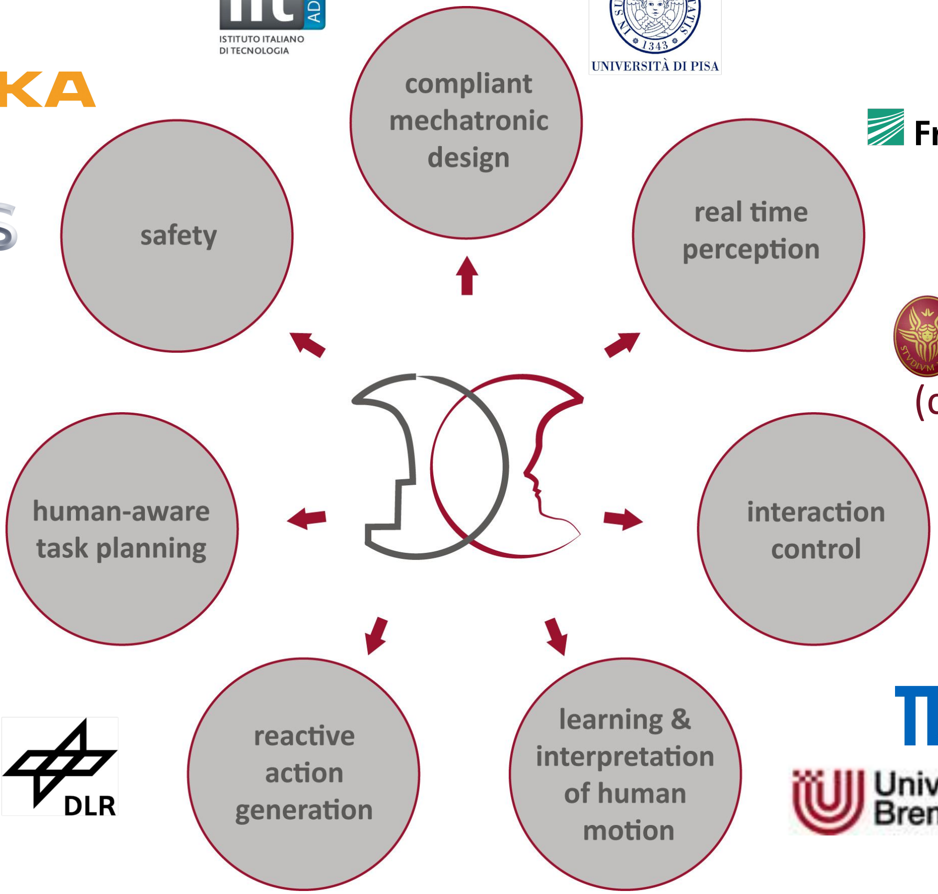
SAPHARI

APPLICATION SCENARIOS SECTORS	ROBOTIC WORKERS	ROBOTIC CO-WORKERS	LOGISTICS ROBOTS	ROBOTS FOR SURVEILLANCE & INTERVENTION	ROBOTS FOR EXPLORATION & INSPECTION	EDUTAINMENT ROBOTS
INDUSTRIAL		▨				
PROFESSIONAL SERVICE		▨				
DOMESTIC SERVICE						
SECURITY						
SPACE						

SAPHARI concept

Place the human at the center of the entire robot development

SAPHARI
Safe and Autonomous
Physical Human-Aware
Robot Interaction



compliant mechatronic design

real time perception

interaction control

learning & interpretation of human motion

reactive action generation

human-aware task planning

safety

IIT ADVR Istituto Italiano di Tecnologia

Università di Pisa

KUKA

Fraunhofer IOSB

EADS

Sapienza Università di Roma
(coordinator)

LAAS-CNRS

DLR

TUM

Universität Bremen

address all essential aspects of safe and intuitive physical interaction between humans and complex human-like robots in a strongly integrated way

Safe physical Human-Robot Interaction

Hierarchy of consistent robot behaviors (BioRob 2012)

Safety

Coexistence

Collaboration

- **integrated design & use** of soft mechanics, actuation, (proprio- and extero-ceptive) sensing, communication, and **control** algorithms

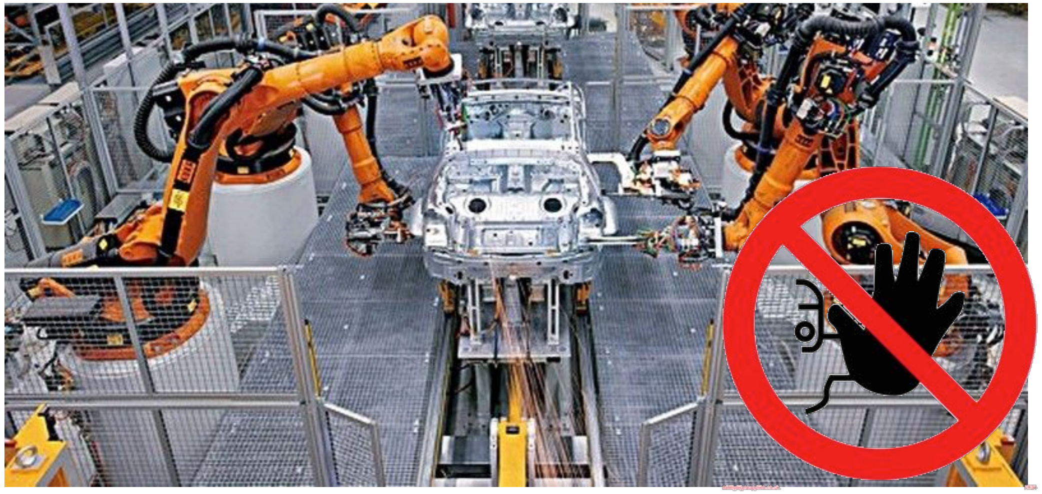
Physical HRI

Hierarchy of consistent behaviors

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



Physical HRI

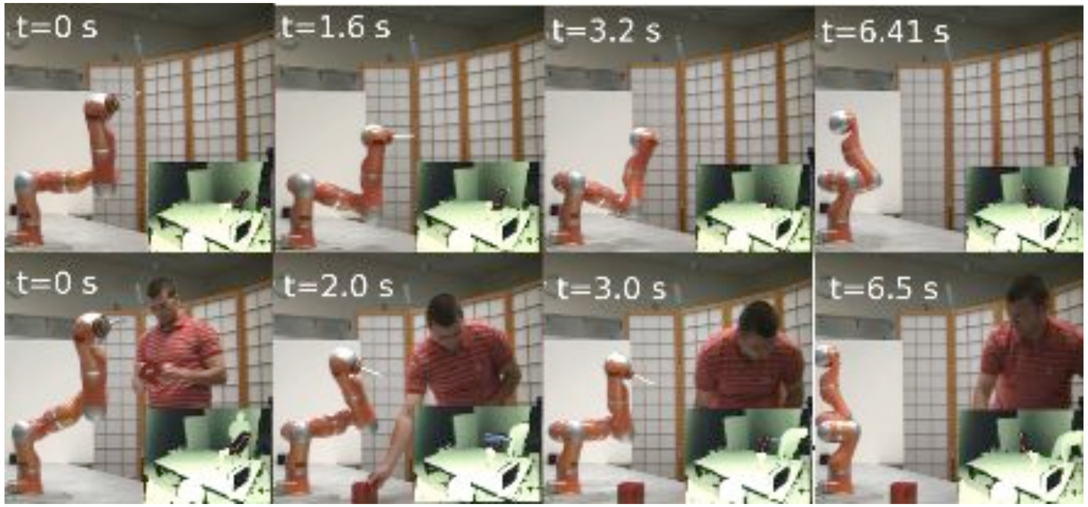
Hierarchy of consistent behaviors

Safety

Coexistence

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

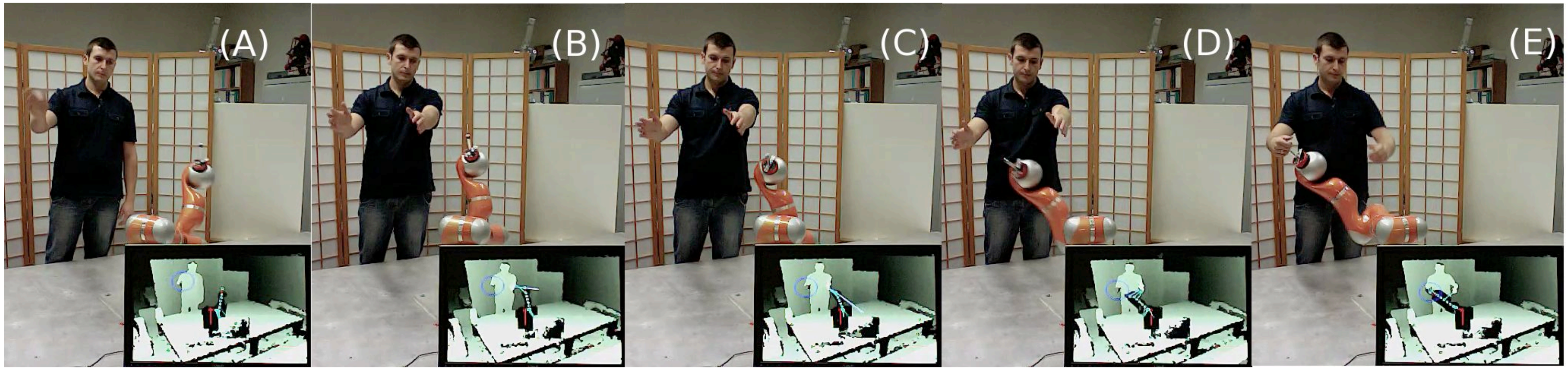

Safety

Coexistence

Collaboration

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

Two modalities that are not mutually exclusive: contactless and physical



Robot dependability

Going beyond reliability in pHRI

- **mechanics: lightweight** construction and inclusion of **compliance**
  - in particular, **variable** stiffness **actuation** devices
- typically, more/additional exteroceptive **sensing** needed
- human-oriented motion **planning** ("legible" robot trajectories)
- **control** strategies with safety objectives/constraints

- prevent, avoid, distinguish, **detect**, **isolate**, and **react to** collisions

Why compliant robots?

Robots with elastic joints

- lightweight but stiff link design reduces robot inertia and preserves kinematic accuracy at end-effector level
- compliant elements can absorb impact energy
  - soft coverage of links (safe bags)
  - elastic transmissions/joints (HD, cables, ...)

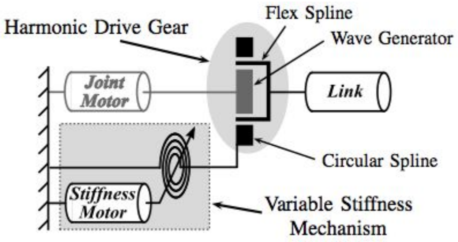
- elastic joints decouple instantaneously the *larger* inertia of the driving motors from the *smaller* inertia of links (where collisions occur!)
  - however, robots with *relatively soft* joints need more *sensing* and better *control* laws to compensate for static deflections and dynamic vibrations

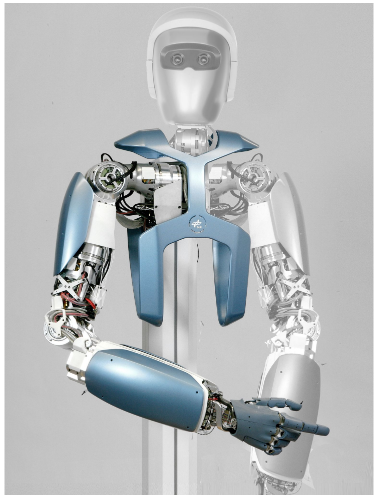
➡ torque-controlled robots (DLR LWR-III, KUKA LWR 4, KUKA iiwa, ...)

Why compliant robots?

Robots with Variable Stiffness Actuation (VSA)

- uncertain/dynamic interaction with the environment requires to adjust robot compliant behavior and/or to control the contact forces
  - passive joint elasticity & active impedance control used in parallel
- nonlinear flexible joints with variable (controlled) stiffness do their best:
  - can be made *stiff when moving slow* (performance), *soft when fast* (safety)
  - enlarge the set of achievable task-oriented compliance matrices
  - feature also: robustness, energy optimization, explosive motion tasks, ...



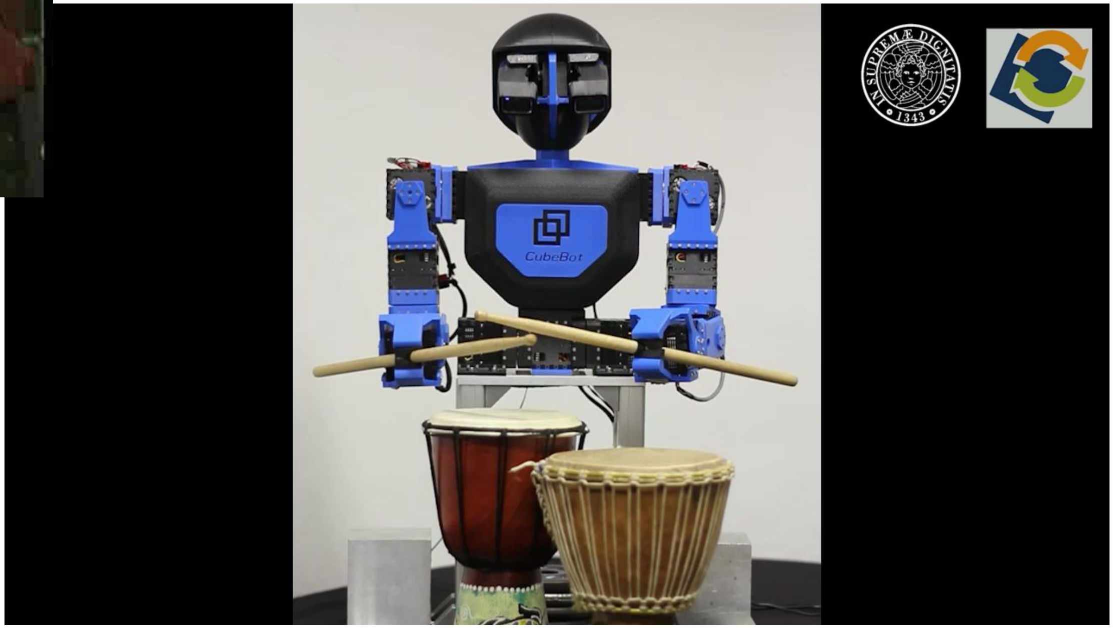


Two compliant robots

KUKA LWR 4 robot with elastic joints vs. VSA-Cube humanoid torso

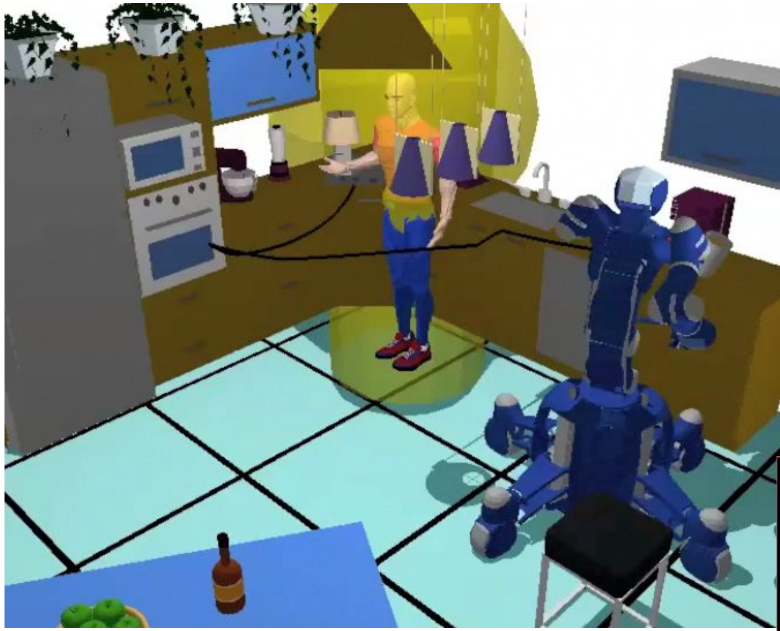
video of impedance control in selected Cartesian directions by DLR

video with various features of torso with low-cost VSA modules by UniPisa



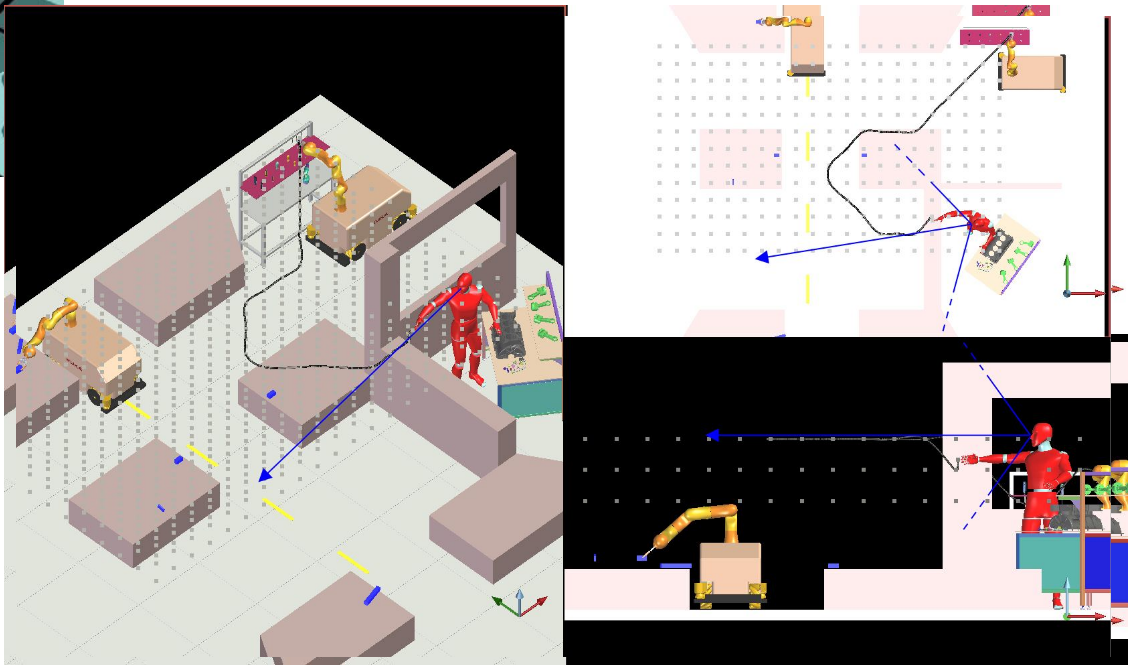
Human-oriented motion planning

Taking into account also human legibility (e.g., field of view)



video of DLR wheeled Justin
@CNRS-LAAS, Toulouse

video of two KUKA OmniRob
mobile manipulators @DIAG, Roma



both are **randomized**
motion planners

Collision detection in industrial robots

Advanced option available only for some robots (ABB, KUKA)

- existing methods allows **only** detection, **not** isolation
  - based on large variations of commanded torques/motor currents

$$\left\|\tau(t_k)-\tau(t_{k-1})\right\| \geq \varepsilon \quad \Leftrightarrow \quad \left|\tau_i(t_k)-\tau_i(t_{k-1})\right| \geq \varepsilon_i$$

for at least one joint

  - based on comparison with nominal torques on desired motion

$$\tau_d = M(q_d)\ddot{q}_d + C(q_d,\dot{q}_d)\dot{q}_d + g(q_d) + f(q_d,\dot{q}_d) \quad \Rightarrow \quad \left\|\tau-\tau_d\right\| \geq \varepsilon$$

  - based on robot state and numerical estimate of acceleration

$$\ddot{q}_N = \frac{d\dot{q}}{dt} \Rightarrow \quad \tau_N = M(q)\ddot{q}_N + C(q,\dot{q})\dot{q} + g(q) + f(q,\dot{q}) \Rightarrow \quad \left\|\tau-\tau_N\right\| \geq \varepsilon$$

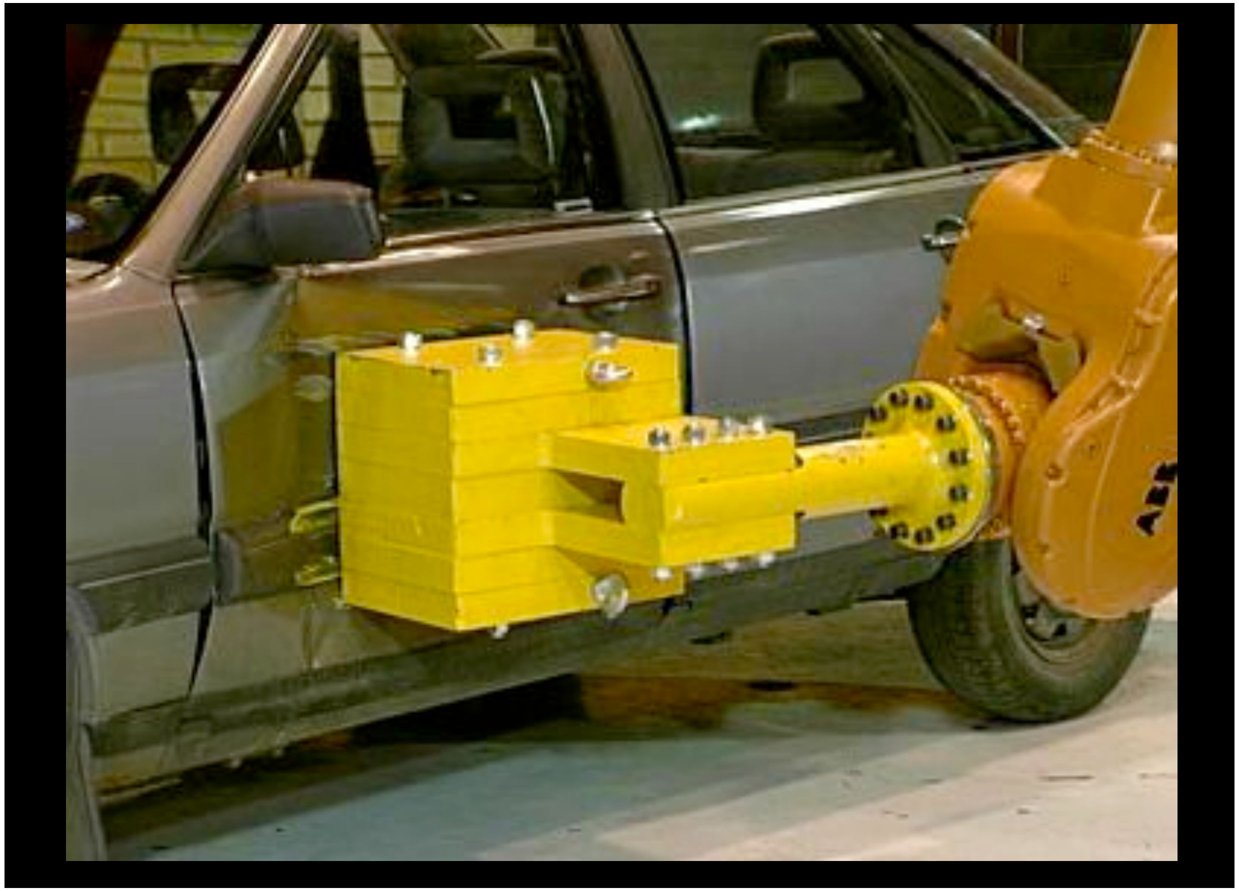
  - based on the parallel simulation of robot dynamics

$$\ddot{q}_C = M^{-1}(q)\left[\tau - C(q,\dot{q})\dot{q} - g(q) - f(q,\dot{q})\right] \Rightarrow \quad \left\|\dot{q}-\dot{q}_C\right\| \geq \varepsilon_{\dot{q}} \quad \left\|q-q_C\right\| \geq \varepsilon_q$$

  - always a comparison of signals or model-based quantities to a **threshold**
- sensitive to actual control law and reference trajectory
- require (noisy) acceleration estimates or (on-line) inversion of the robot inertia matrix

ABB collision detection

ABB IRB 7600 robot with heavy payload



video by ABB

- the only feasible robot reaction is to stop!

Collision handling for safety

Detection of undesired collisions and robot reaction

- **phases**: pre-impact (avoidance), impact (detection), and post-impact (reaction)
- collision detection **using only** on-board robot **proprioceptive** sensors (encoders)
- safe reaction (apart from stopping the robot) requires not only “detection” but also “isolation” (which link has collided)
- monitoring of possible collisions should be **continuously active**
- collisions may occur at **any (unknown) place** along the whole robotic structure
- working assumptions
  - one single collision at a time
  - manipulator as an open kinematic chain
  - first, **rigid** joints case ⇒ then, extension to **flexible** joints

any control torque

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} + \boldsymbol{\tau}_K = \boldsymbol{\tau}_{\text{tot}}$$

inertia matrix

Coriolis/centrifugal terms

gravity terms

joint torque due to link collision

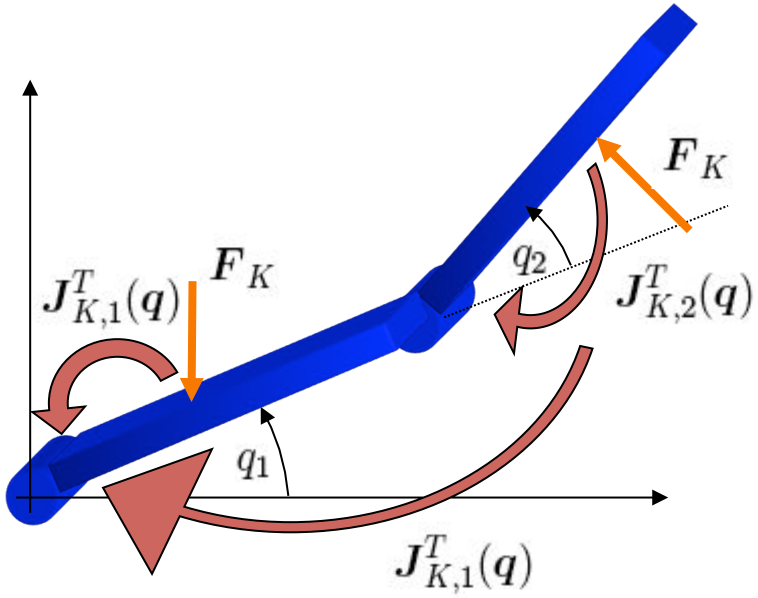
transpose of the Jacobian associated to the contact point

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

Analysis of a collision

Existence of dynamic couplings

$$V_K = \begin{bmatrix} v_K \\ \omega_K \end{bmatrix} = \begin{bmatrix} J_{K,\mathrm{lin}}(q) \\ J_{K,\mathrm{ang}}(q) \end{bmatrix} \dot{q} = J_K(q)\dot{q} \in \mathbb{R}^6 \qquad F_K = \begin{bmatrix} f_K \\ m_K \end{bmatrix} \in \mathbb{R}^6$$



in **static** conditions:
a contact force/torque on the *i*-th link is balanced ONLY by torques at preceding joints $j \leq i$

in **dynamic** conditions:
a contact force/torque on the *i*-th link produces accelerations at ALL joints

Relevant physical properties

Exploiting the robot dynamics

- total energy and its variation

$$E = T + U = \frac{1}{2}\dot{q}^T M(q)\dot{q} + U_g(q) \qquad \boxed{\dot{E} = \dot{q}^T \boldsymbol{\tau}_{\mathrm{tot}}}$$

- generalized moments and their decoupled dynamics

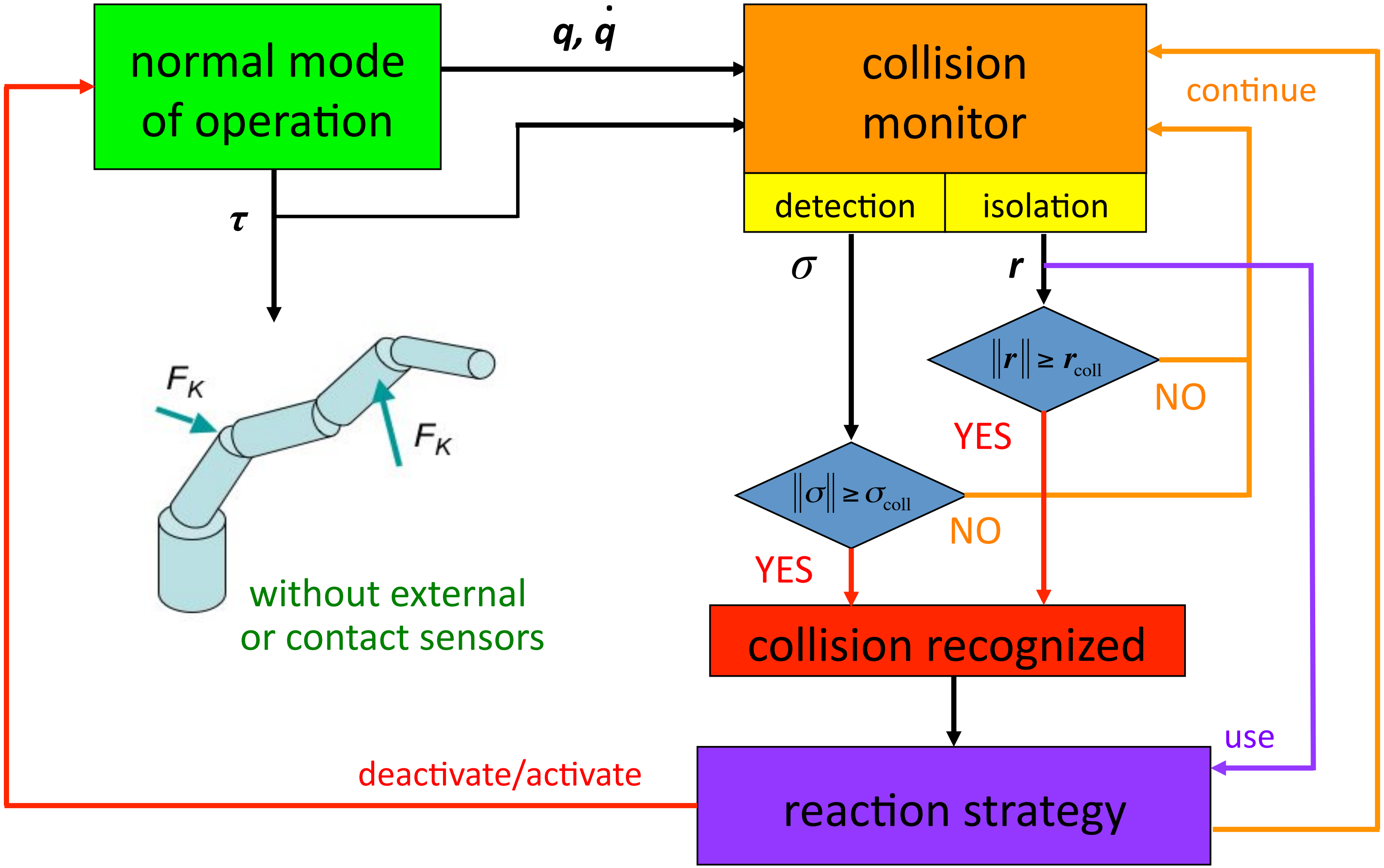
$$p = M(q)\dot{q}$$

$$\boxed{\dot{p} = \boldsymbol{\tau}_{\mathrm{tot}}} + C^T(q,\dot{q})\dot{q} - g(q)$$

using the skew-symmetric property $\dot{M}(q) = C(q,\dot{q}) + C^T(q,\dot{q})$

Monitoring collisions

General block diagram



Energy-based detection of collisions

Only for detection

- scalar residual (computable, e.g., by N-E algorithm)

$$\sigma(t) = k_D \left[E(t) - \int_0^t \left(\dot{\boldsymbol{q}}^T \boldsymbol{\tau} + \sigma \right) ds - E(0) \right]$$

$$\sigma(0) = 0$$

- … and its dynamics (needed only for analysis)

$$\dot{\sigma} = -k_D\,\sigma + k_D \boxed{\dot{\boldsymbol{q}}^T \boldsymbol{\tau}_K}$$

a stable first-order linear filter, excited by a collision!

Analysis of the energy-based method

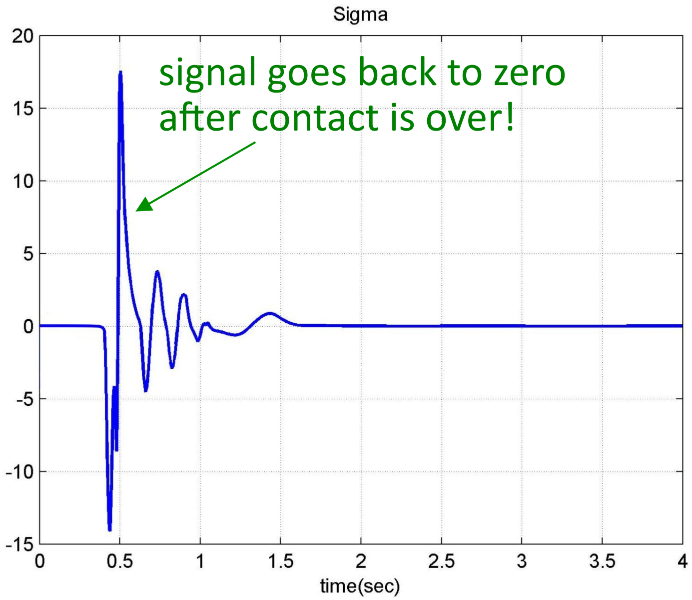
Only for **detection**

- very simple scheme (scalar signal)
- can only detect the presence of collision forces/torques (wrenches) that produce work on linear/angular velocities (twists) at the contact
- does not work when the robot stands still…

$$\dot{q}^T \boldsymbol{\tau}_K = \dot{q}^T \boldsymbol{J}_K^T(\boldsymbol{q}) \boldsymbol{F}_K = \boldsymbol{V}_K^T \boldsymbol{F}_K = 0 \iff \boxed{\boldsymbol{V}_K \perp \boldsymbol{F}_K}$$

$$\boldsymbol{V}_K = \begin{bmatrix} \boldsymbol{v}_K \\ \boldsymbol{\omega}_K \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{K,\text{lin}}(\boldsymbol{q}) \\ \boldsymbol{J}_{K,\text{ang}}(\boldsymbol{q}) \end{bmatrix} \dot{\boldsymbol{q}} = \boldsymbol{J}_K(\boldsymbol{q})\dot{\boldsymbol{q}} \in \mathbb{R}^6$$

$$\boldsymbol{F}_K = \begin{bmatrix} \boldsymbol{f}_K \\ \boldsymbol{m}_K \end{bmatrix} \in \mathbb{R}^6$$



signal goes back to zero after contact is over!

Momentum-based isolation of collisions

Both for detection and isolation

- residual vector (computable...)

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

$$\boldsymbol{r}(0) = \boldsymbol{0} \qquad \boldsymbol{K}_I > 0 \qquad \boldsymbol{p} = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}}$$

(diagonal)

- ... and its decoupled dynamics

$$\dot{\boldsymbol{r}} = -\boldsymbol{K}_I \boldsymbol{r} + \boldsymbol{K}_I \boxed{\boldsymbol{\tau}_K} \qquad \frac{r_j(s)}{\tau_{K,j}(s)} = \frac{K_{I,j}}{s + K_{I,j}}$$

$$j = 1, \ldots, N$$

N independent, stable, first-order linear filters, excited by a collision!

(all residuals go back to zero if there is no longer contact = post-impact phase)

Analysis of the momentum-based method

Both for detection and isolation

- ideal situation (no noise/uncertainties)

$$\boldsymbol{K}_I \to \infty \quad \Rightarrow \quad \boxed{\boldsymbol{r} \approx \boldsymbol{\tau}_K}$$

- **isolation property**: collision has occurred in an area located up to the i-th link if

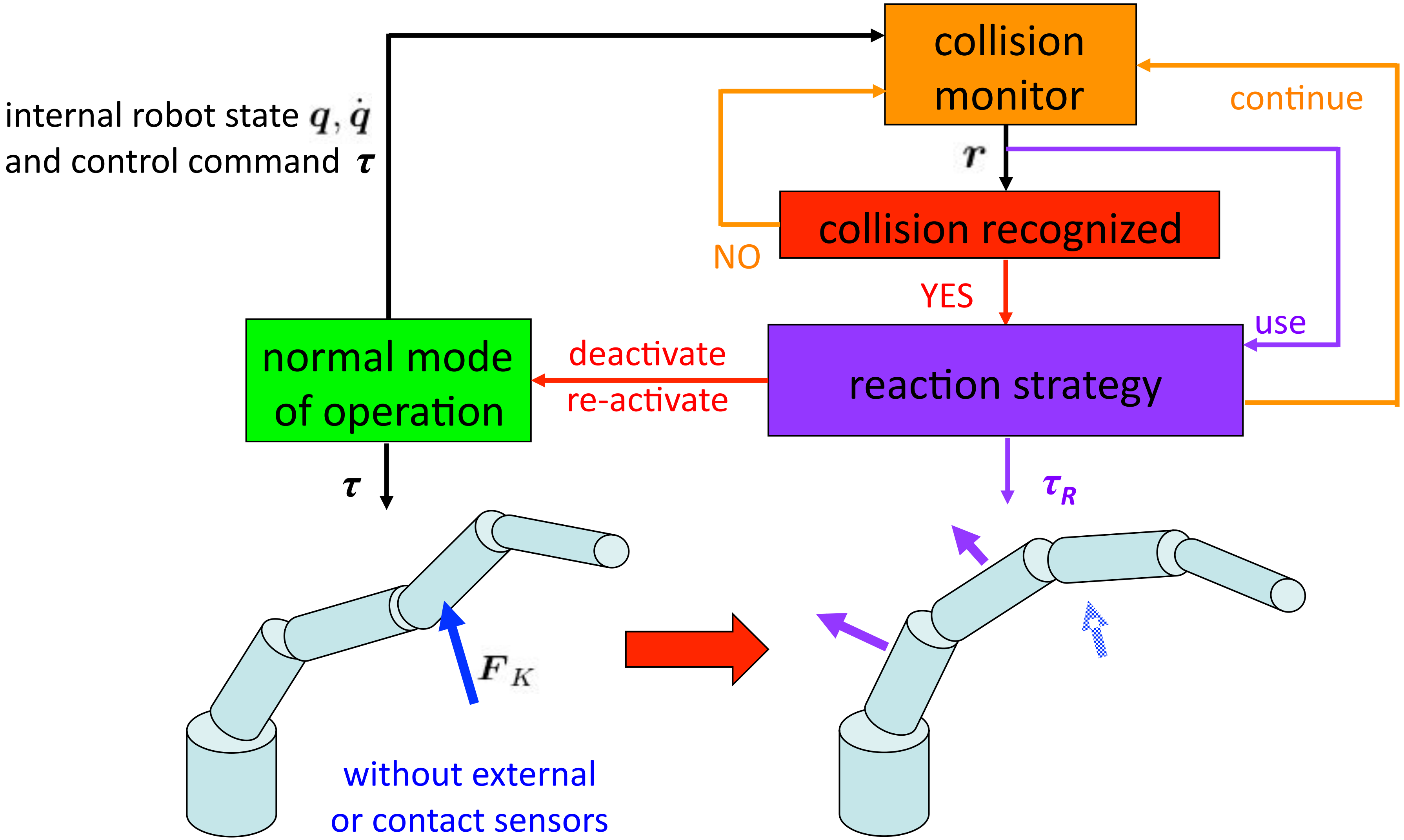
$$\boldsymbol{r} = \begin{bmatrix} * & \dots & * & * & \boxed{0 \qquad \dots \qquad 0} \end{bmatrix}^T$$

$$\begin{array}{ccc} \uparrow & & \uparrow \\ \textcircled{i}+1 & \dots & N \end{array}$$

- **residual vector** contains directional information on the torque at the robot joints resulting from the link collision (useful for robot reaction in post-impact phase)

Collision reaction

Based on computed **residuals**



internal robot state $\boldsymbol{q}, \dot{\boldsymbol{q}}$
and control command $\boldsymbol{\tau}$

collision monitor

$\boldsymbol{r}$

collision recognized

NO

YES

continue

use

normal mode of operation

deactivate
re-activate

reaction strategy

$\boldsymbol{\tau}$

$\boldsymbol{\tau}_R$

$\boldsymbol{F}_K$

without external
or contact sensors

Robot reaction strategy

Basic methods for rigid robots

- "zero-gravity" control in any operative mode

$$\boldsymbol{\tau} = \boldsymbol{\tau}' + \boldsymbol{g}(\boldsymbol{q})$$

- upon detection of a collision ($\boldsymbol{r}$ is over some threshold)
  - **no** reaction (strategy 0): robot continues its planned motion …
  - **stop** robot motion (strategy 1): either by braking or by stopping the motion reference generator and switching to a high-gain position control law
  - **reflex* strategy**: switch to a residual-based control law

$$\boldsymbol{\tau}' = \boldsymbol{K}_R \boldsymbol{r} \qquad \boldsymbol{K}_R > 0 \qquad \text{(diagonal)}$$

"joint torque command in the same direction of collision torque"

* = in robots with transmission/joint elasticity, the reflex strategy can be implemented in different ways (strategies 2,3,4)

Analysis of the reflex strategy

In ideal conditions for rigid robots

- this control strategy is equivalent to a reduction of the effective robot inertia, as seen by the collision force/torque

$$(\boldsymbol{I} + \boldsymbol{K}_R)^{-1} \left(\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} \right) = \boldsymbol{\tau}_K$$

“a lighter robot that can be more easily pushed way”

from a cow …

… to a frog!

Collision detection and isolation

Extension to robots with elastic joints

- dynamic model of robots with elastic joints

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

joint torque due to link collision

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

motor torques commands

elastic torques at the joints

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

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

lightweight (14 kg)
7R robot with
harmonic drives
(elastic joints)
and modular
structure

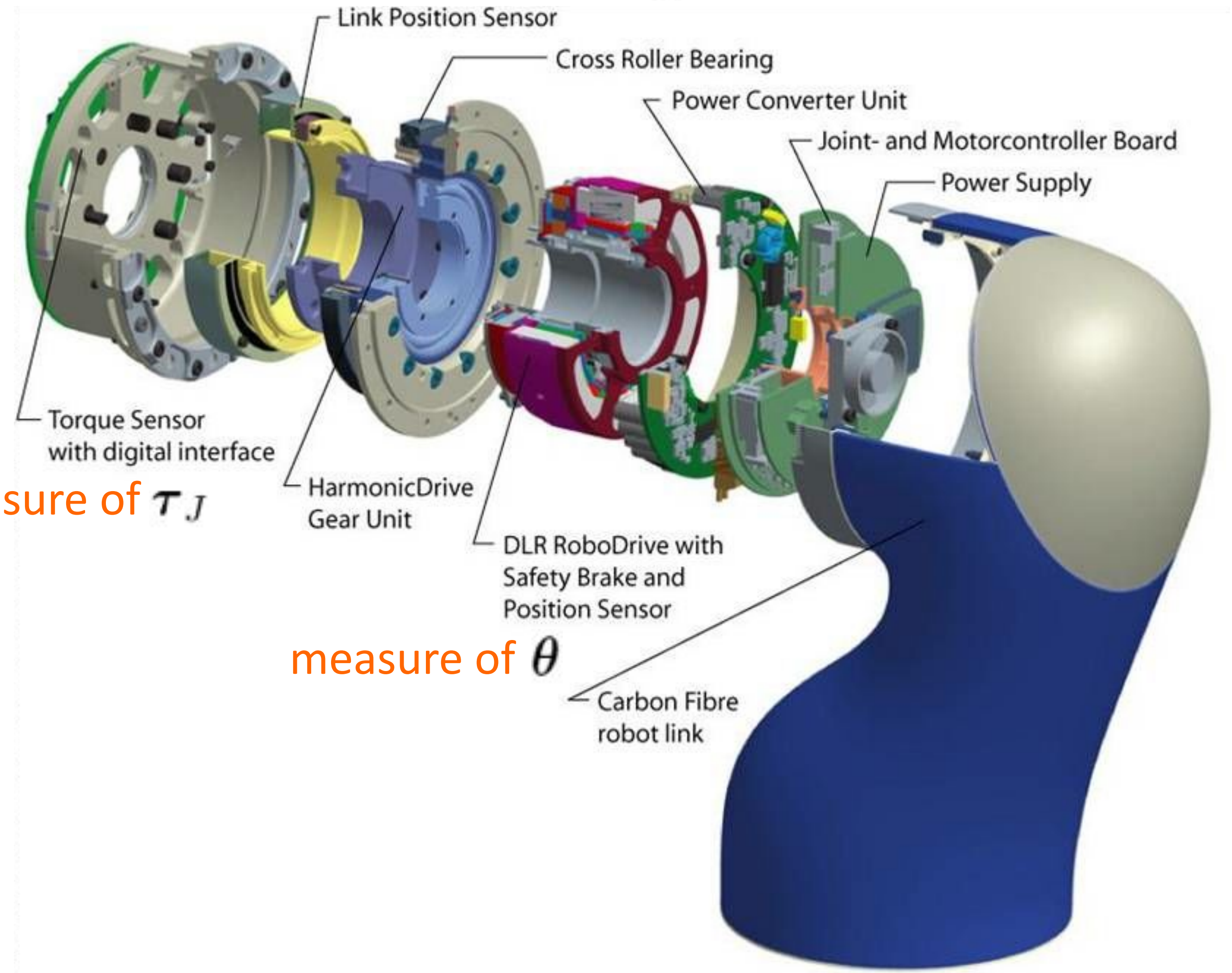
$$\boxed{\tau \rightarrow \tau_J}$$

"replace the commanded torque to the motors with the elastic torque measured at the joints"

$$r_{EJ}(t) = K_I \left[p(t) - \int_0^t \left(\tau_J + C^T(q,\dot{q})\dot{q} - g(q) - r_{EJ} \right) ds \right]$$

Sensorization of the DLR LWR-III robot

Exploded view of a robot joint

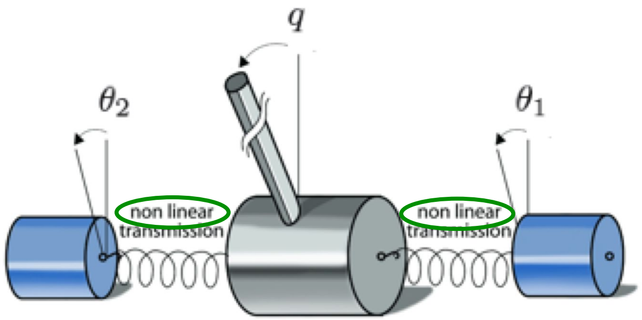


Collision detection and isolation — other scheme

Without a joint torque sensor – for robots with VSA or with elastic joints

- robots with (antagonistic) Variable Stiffness Actuation

$$
\begin{aligned}
B\ddot{\theta}_1 + D\dot{\theta}_1 + 2\tau_{J1} &= \tau_1 \\
B\ddot{\theta}_2 + D\dot{\theta}_2 + 2\tau_{J2} &= \tau_2 \\
M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) &= 2(\tau_{J1} + \tau_{J1}) + \tau_K
\end{aligned}
$$



- define the total momentum (two actuators per joint + links) as

$$\boxed{p_{\text{sum}}} = B(\dot{\theta}_1 + \dot{\theta}_2) + M(q)\dot{q}$$

- a residual can also be defined as

$$r = K_I\left(p_{\text{sum}} - \int_0^t \left(r + C^T(q,\dot{q})\dot{q} - g(q) + \tau_1 + \tau_2 - D(\dot{\theta}_1 + \dot{\theta}_2)\right) ds\right)$$

"no flexible (transmission) torque measure is needed..."

$$\Rightarrow \quad \dot{r} = K_I\left(\tau_K - r\right)$$

- an alternative scheme for robots with elastic joints is derived similarly

Control of DLR LWR-III robot

A robot with elastic joints

- general control law using full state feedback
  (motor position and velocity, joint elastic torque and its derivative)

$$\boldsymbol{\tau} = \boldsymbol{K}_P(\boldsymbol{\theta}_d - \boldsymbol{\theta}) - \boldsymbol{K}_D\dot{\boldsymbol{\theta}} + \boldsymbol{K}_{P\tau}(\boldsymbol{\tau}_{J,d} - \boldsymbol{\tau}_J) - \boldsymbol{K}_{D\tau}\dot{\boldsymbol{\tau}}_J + \boldsymbol{\tau}_{J,d}$$

motor position error

elastic joint torque error

elastic joint torque feedforward command

- “zero-gravity” condition can be realized only in an approximate (quasi-static) way, using just motor position measures

$$\bar{\boldsymbol{g}}(\boldsymbol{\theta}) = \boldsymbol{g}(\boldsymbol{q}), \quad \forall(\boldsymbol{\theta}, \boldsymbol{q}) \in \Omega := \{(\boldsymbol{\theta}, \boldsymbol{q}) |\, \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q}) = \boldsymbol{g}(\boldsymbol{q})\}$$

motor position

link position

(diagonal) matrix of joint stiffness

Robot reaction strategies

Specific for robots with elastic joints

- strategy 2: floating reaction (robot ≈ in “zero-gravity”)

$$\boldsymbol{\tau}_{J,d} = \bar{\boldsymbol{g}}(\boldsymbol{\theta}) \qquad \boldsymbol{K}_P = 0$$

- strategy 3: reflex torque reaction (closest to the rigid case)

$$\boldsymbol{\tau}_{J,d} = \boldsymbol{K}_R \boldsymbol{r}_{\mathrm{EJ}} + \bar{\boldsymbol{g}}(\boldsymbol{\theta}) \qquad \boldsymbol{K}_P = 0$$

- strategy 4: admittance mode reaction (residual is used as the new reference for the motor velocity)

$$\boldsymbol{\tau}_{J,d} = \bar{\boldsymbol{g}}(\boldsymbol{\theta}) \qquad \dot{\boldsymbol{\theta}}_d = \boldsymbol{K}_R \boldsymbol{r}_{\mathrm{EJ}}$$

- further possible reaction strategies (rigid or elastic case)
  - based on impedance control
  - sequence of strategies (e.g., 4+2)
  - time scaling: stop/reprise of reference trajectory, keeping the path
  - Cartesian task preservation (exploits robot redundancy by projecting reaction torque in a task-related dynamic null space)

First experiments with DLR LWR-III robot

Case of a “dummy” head (early 2006)

dummy head equipped
with an accelerometer

robot straighten horizontally,
mostly motion of joint 1 @30°/sec

Dummy head impacts

Two of the reaction strategies

video

video

strategy 0: **no** reaction

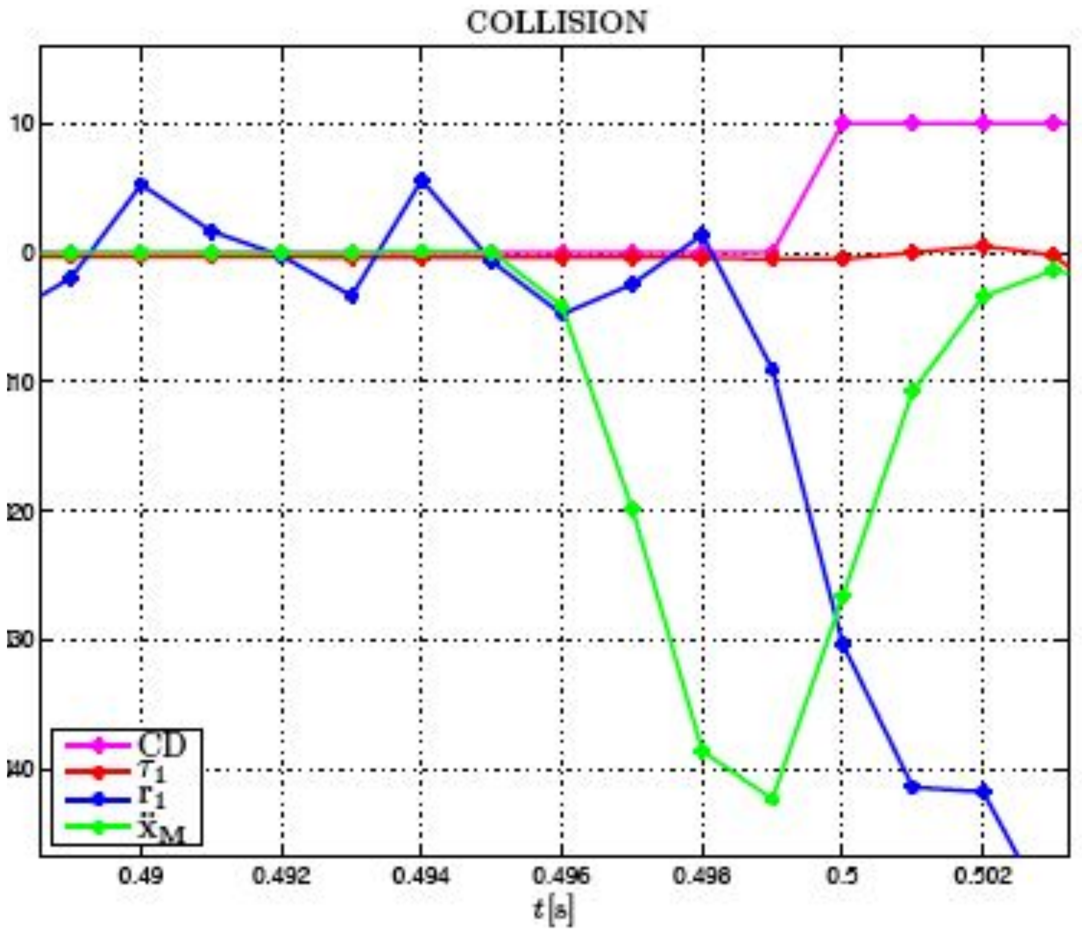
planned trajectory ends just after the position of the dummy head

strategy 2: **floating** reaction

impact velocity is rather low here and the robot stops quite immediately

Delay in collision detection

Impact with “dummy” head



2-4 msec!

measured (elastic) joint torque

residual r_1

0/1 index for detection

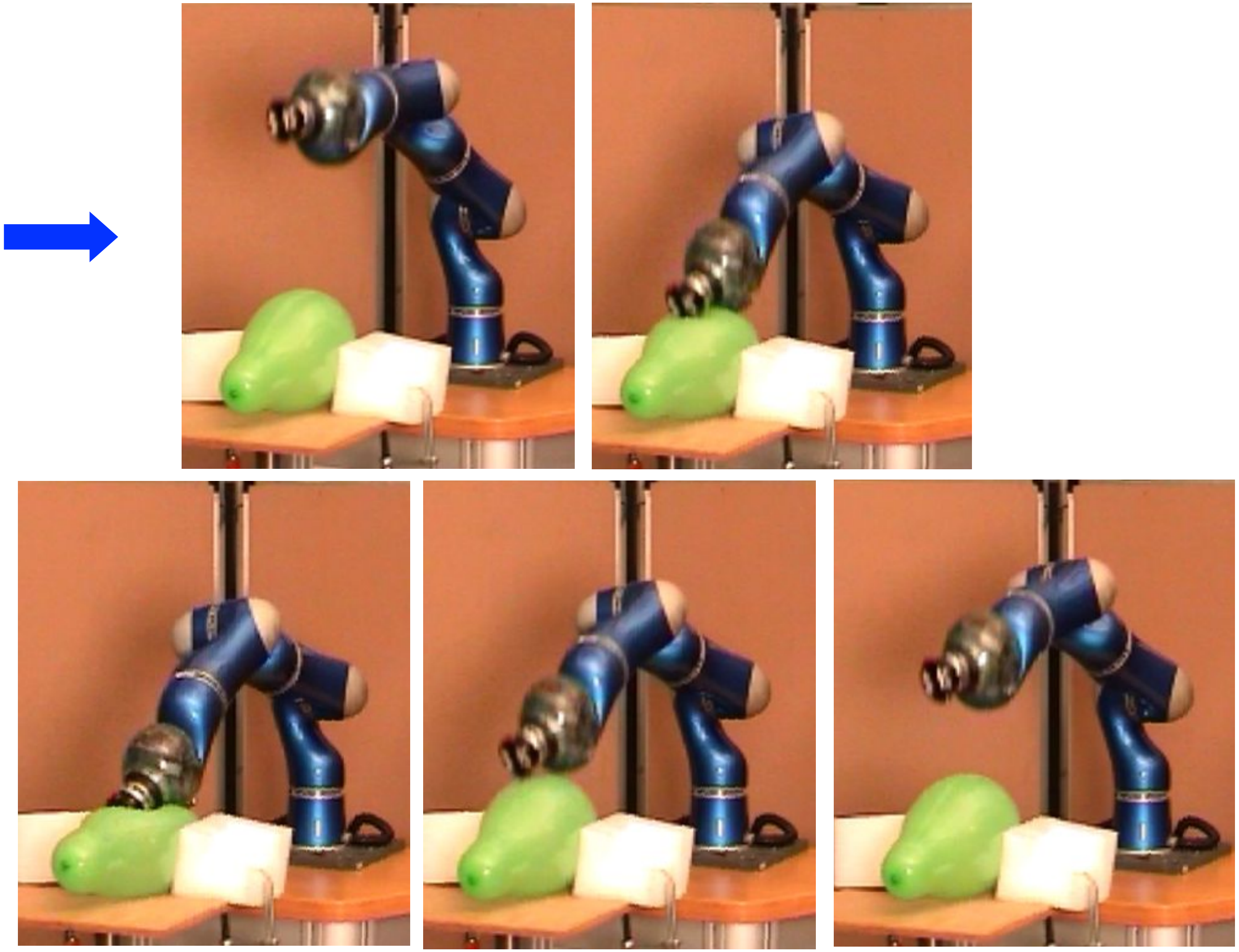
dummy head acceleration

gain K_I = diag{25}

threshold = 5-10% of max rated torque

Balloon impacts

In IROS 2006 paper



case study for repeatable
comparison of different
reaction strategies
(at high speed conditions)

Balloon impacts

One of the reaction strategies

video

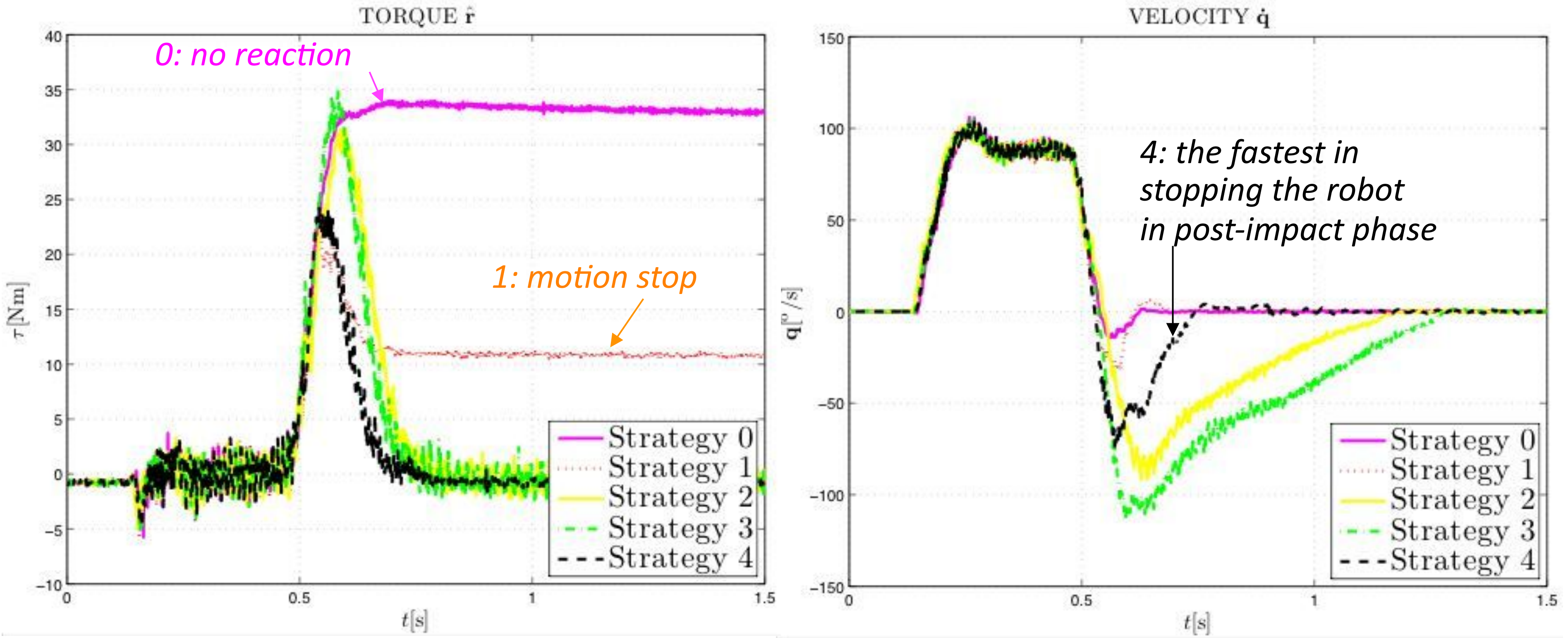
coordinated
joint motion
@100°/sec

strategy 4: admittance mode reaction

Experimental comparison

Robot **reaction strategies** in balloon impact

- residual and velocity at joint 4 with various reaction strategies



impact at 100°/sec with coordinated joint motion

Human-robot impacts

At moderate speed, then handling successive contacts

- first impact @60°/sec

video

video

strategy 4: admittance mode

$$\dot{\boldsymbol{q}}_r = \boldsymbol{K}_Q \boldsymbol{r}$$

strategy 3: reflex torque

$$\boldsymbol{\tau} = \boldsymbol{K}_R \boldsymbol{r}$$

Human-robot impacts

At **maximum** speed, then handling successive contacts

- first impact @90°/sec

video

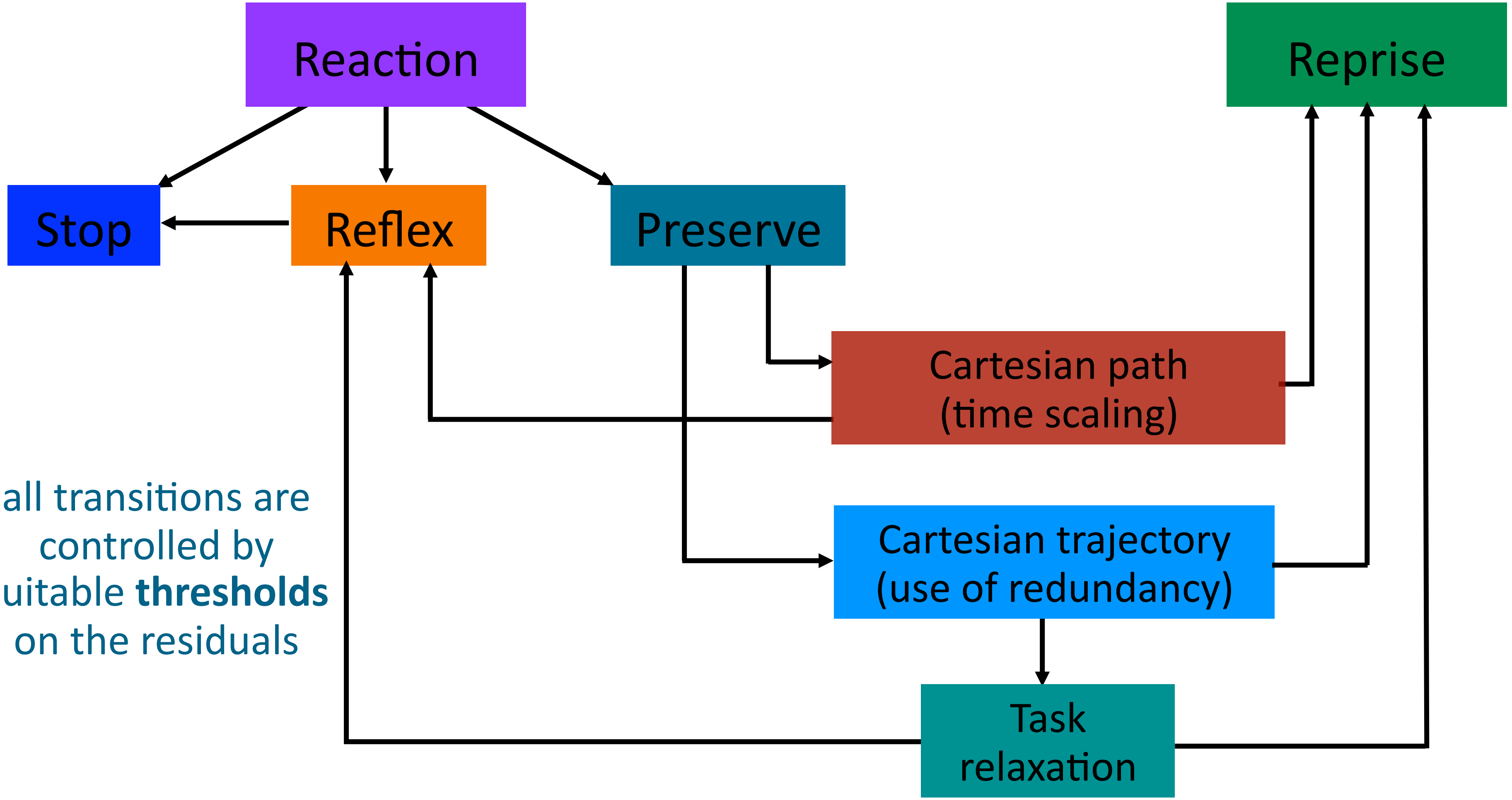
strategy 3: reflex torque

$$\boldsymbol{\tau} = \boldsymbol{K}_R \boldsymbol{r}$$

Collision reaction

Portfolio of possible robot reactions

residual amplitude ∝ severity level of collision



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

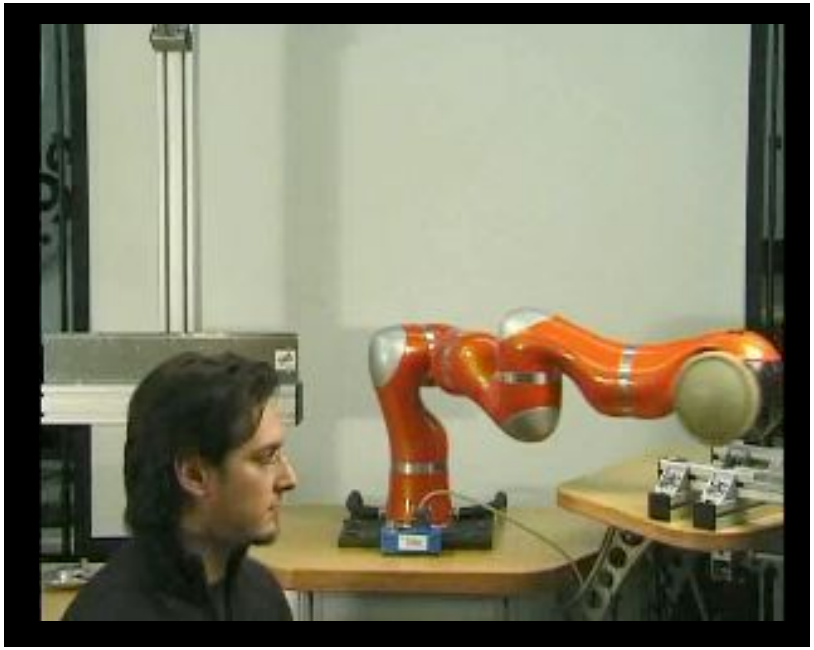
Collision reaction

Further examples (IROS 2008)

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

results from
PHRIENDS project

video



- the perfect “volunteer” is Sami Haddadin!

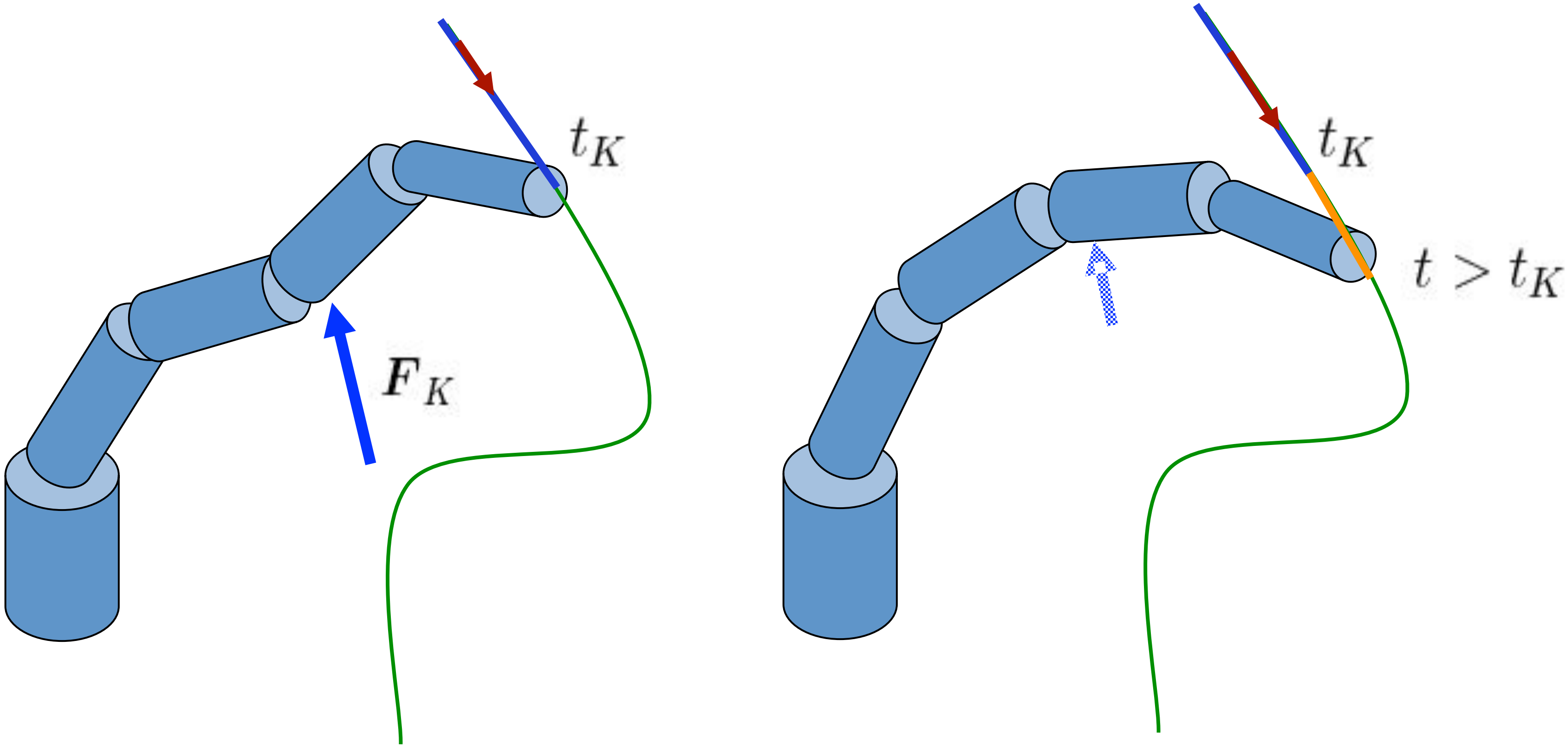
video

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

Use of kinematic redundancy

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

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



Task kinematics

At the second-order differential level

- task coordinates $x \in \mathrm{R}^m$ with $\boxed{m < n}$ (redundancy)

$$\dot{x} = J(q)\dot{q} \qquad \ddot{x} = \dot{J}(q)\dot{q} + J(q)\ddot{q}$$

- (all) generalized inverses of the task Jacobian

$$J(q)G(q)J(q) = J(q), \qquad \forall q$$

- all joint accelerations realizing a desired task acceleration (in a given robot state)

$$\ddot{q} = G(q)(\boxed{\ddot{x}} - \dot{J}(q)\dot{q}) + (I - G(q)J(q))\boxed{\ddot{q}_0}$$

arbitrary joint acceleration

Dynamic redundancy resolution

General approach (includes Khatib's dynamic consistency)

- set for compactness $n(q,\dot{q}) = C(q,\dot{q})\dot{q} + g(q)$
- all joint torques realizing accurate control of the desired (Cartesian) task

$$\begin{aligned}\tau = {} & M(q)G(q)\left[\overset{\ddot{x}_d + K_P e + K_D\dot{e}}{\overset{\downarrow}{\boxed{\ddot{x}}}} - \dot{J}(q)\dot{q} + J(q)M^{-1}(q)n(q,\dot{q})\right]\\ & + \underbrace{M(q)(I - G(q)J(q))M^{-1}(q)}_{} \underset{\uparrow}{\boxed{\tau_0}}\end{aligned}$$

projection matrix in the dynamic null space of J

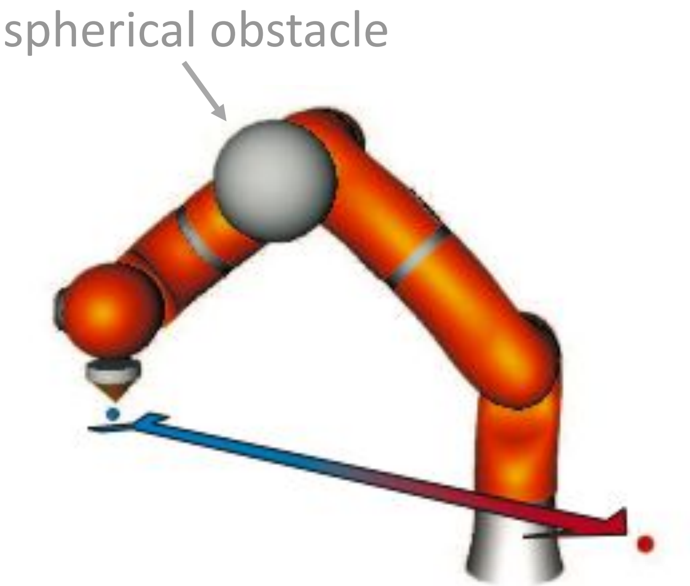
arbitrary joint torque available for reaction to collisions

for any generalized inverse *G*, the joint torque has two contributions: one imposes the task acceleration control, the other does not affect it

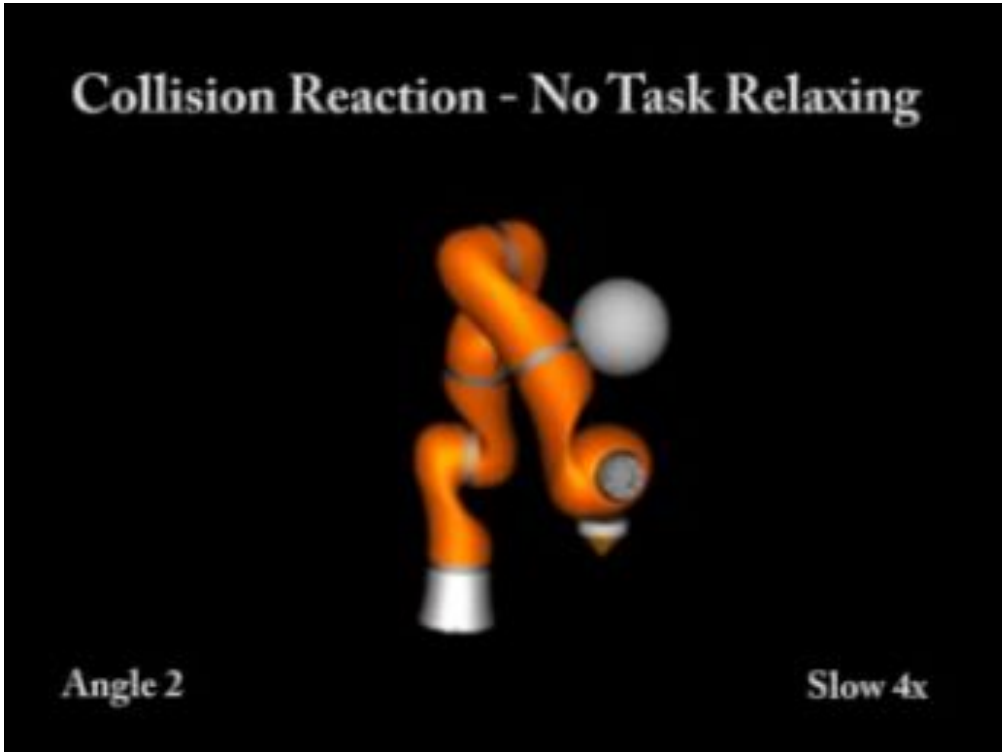
Cartesian task preservation

While handling collision (IROS 2008b)

- wish to preserve whole Cartesian task (end-effector position/orientation), by reacting to collisions using only dynamic self-motions in the joint space
- if the residual ($\propto$ contact force) grows too large, orientation is relaxed first and then, if necessary, the full task is abandoned (priority is given to safety)

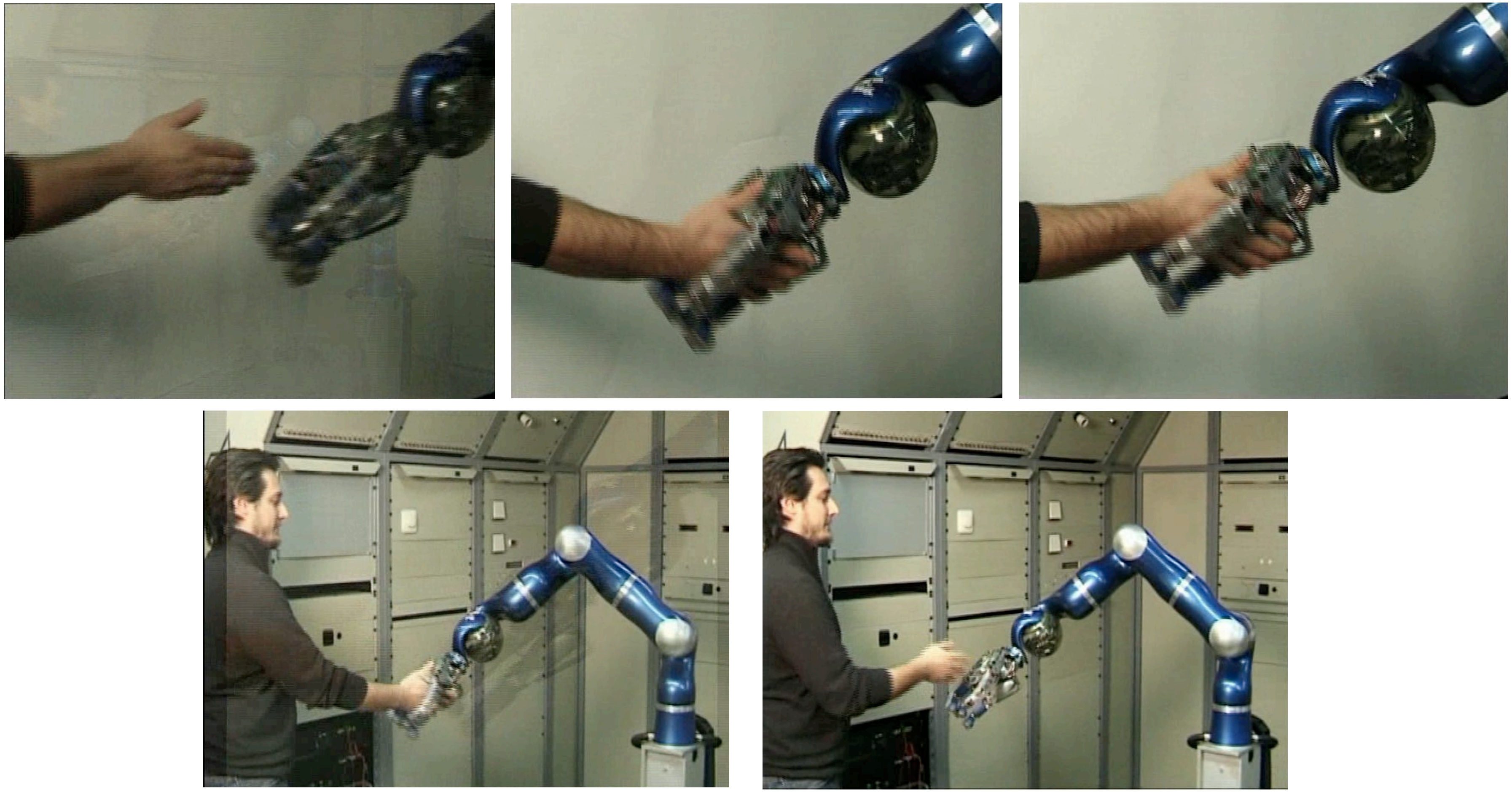


video



Combined use

6D F/T sensor at the wrist + (proprio-ceptive) residuals

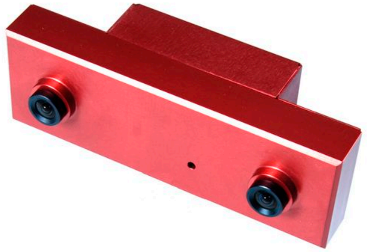


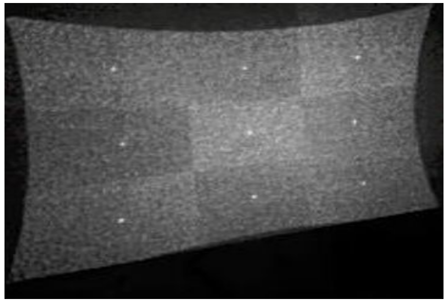
- enables distinguishing intentional interactions vs. unexpected collisions
- it is sufficient to include the **F/T measure** in the expression of the residual...

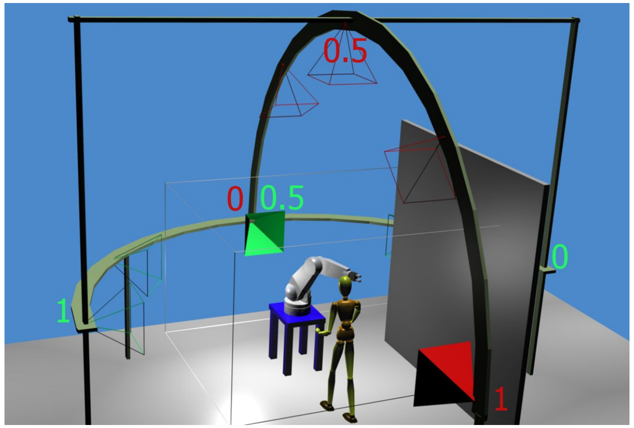
Collision avoidance

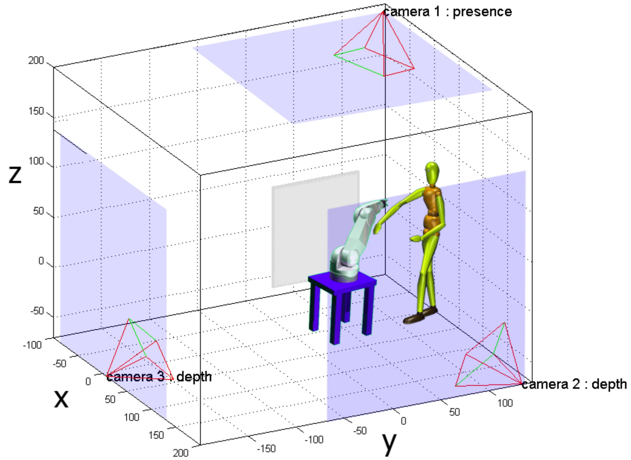
Using extero-ceptive sensors to monitor robot workspace (ICRA 2010)

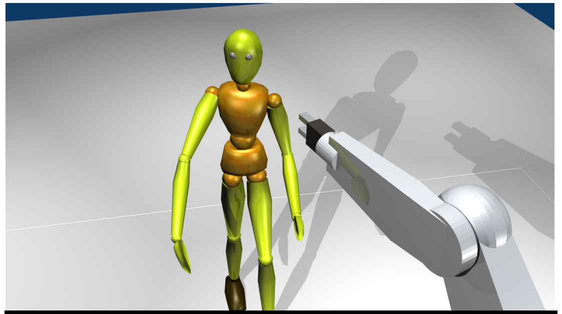
- **external sensing:** stereo-camera, TOF, structured light, **RGB-Depth**, laser, presence, ... placed optimally to minimize occlusions (robot has to be removed from images)

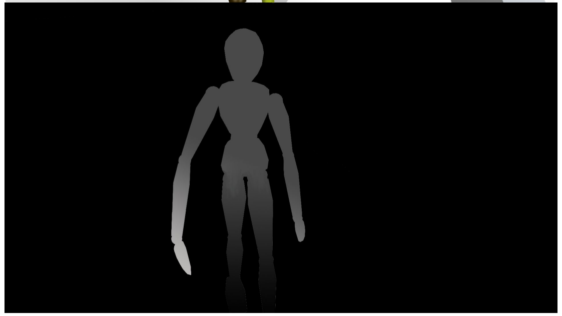






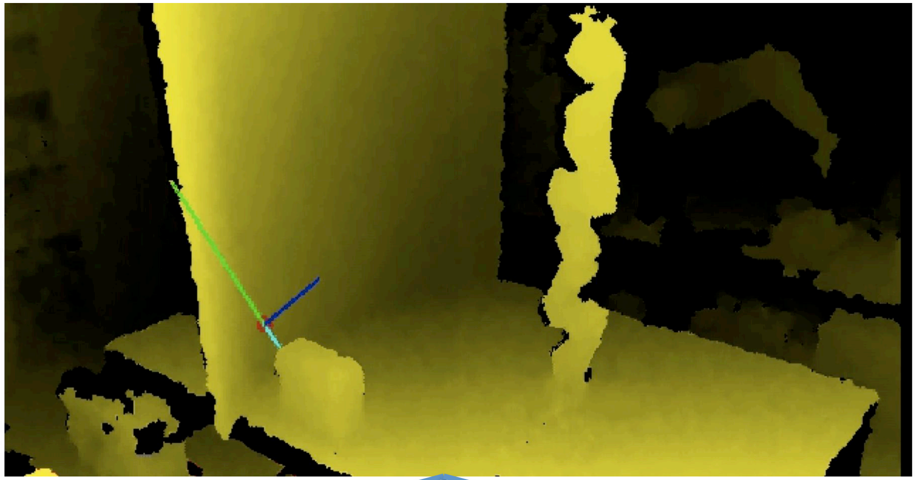






Depth image

How to use it?



Configuration Space

Depth Space

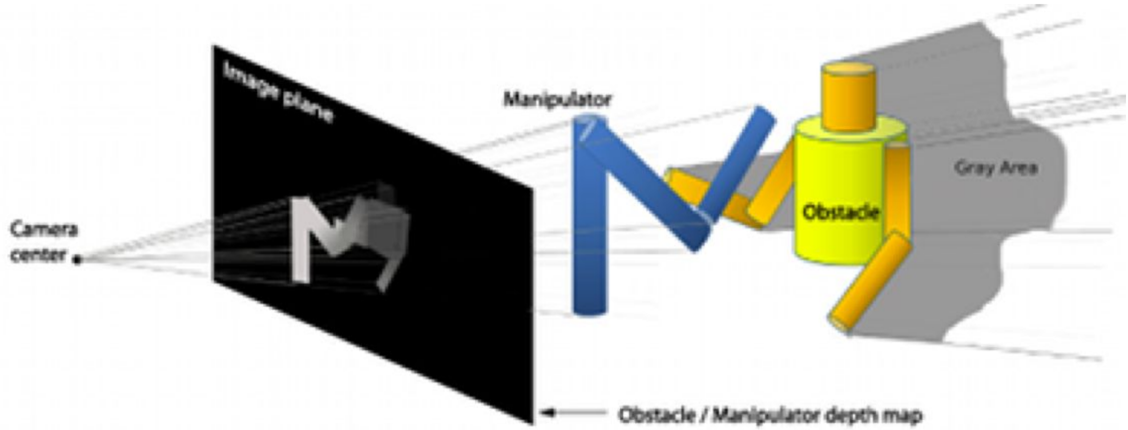
Cartesian Space

Depth space

A 2.5-dimensional space

- non-homogeneous 2.5 dimensional space
  - (x,y) position of the point in the image plane [pixel]
  - d depth of the point w.r.t. the image plane [m]
- depth space is modeled as a pin-hole sensor
- point in Cartesian reference frame $\boldsymbol{P}_R = (x_R, y_R, z_R)$
- point in sensor frame $\boldsymbol{P}_C = \boldsymbol{R}\boldsymbol{P}_R + \boldsymbol{t} = (x_C, y_C, z_C)$
- point in depth space

$$
\begin{aligned}
p_x &= \frac{x_C f s_x}{z_C} + c_x \\
p_y &= \frac{y_C f s_y}{z_C} + c_y \\
d_p &= z_C
\end{aligned}
$$



Depth space

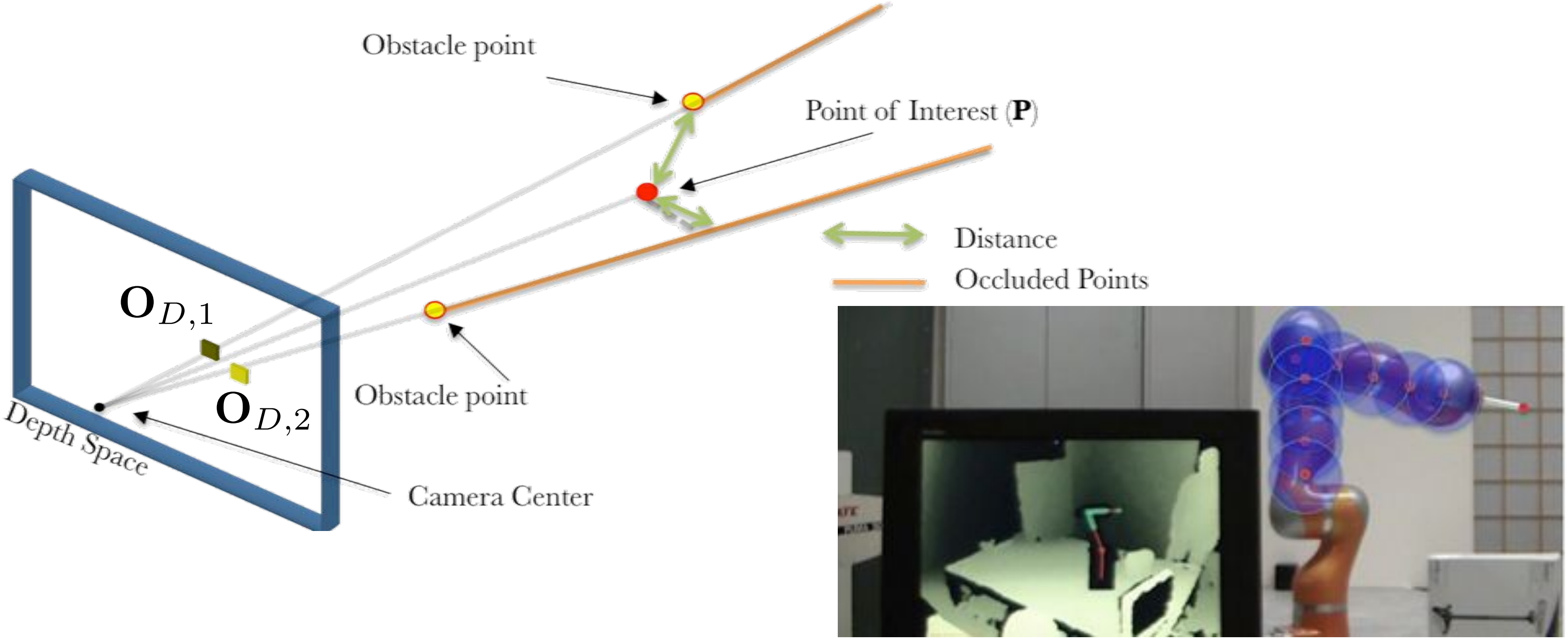
Distance evaluation

- distance between a point of interest $\boldsymbol{P}_D = (p_x, p_y, d_p)$
  and an obstacle point $\mathbf{O}_D = (o_x, o_y, d_o)$

$$\boxed{\text{dist}(\boldsymbol{P}, \mathbf{O}) = \sqrt{v_x^2 + v_y^2 + v_z^2}}$$

$$v_x = \frac{(o_x - c_x)d_o - (p_x - c_x)d_p}{f s_x} \quad v_y = \frac{(o_y - c_y)d_o - (p_y - c_y)d_p}{f s_y} \quad v_z = d_o - d_p$$

(if obstacle point is closer than point of interest, set $d_o = d_p$)

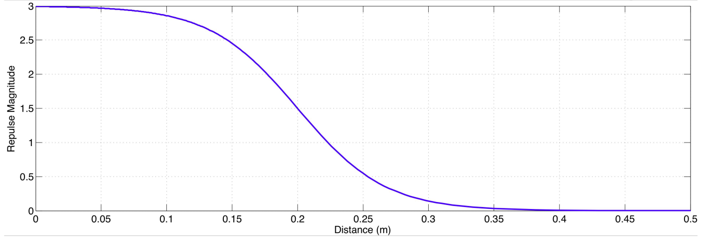


Repulsive vector

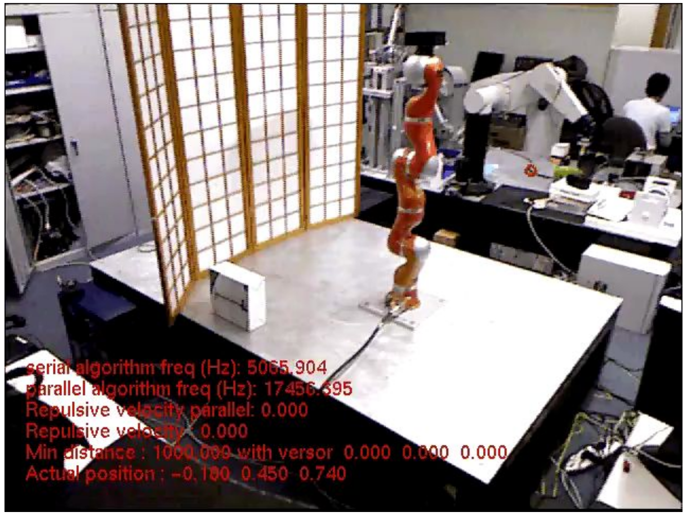
A version of artificial potentials

- repulsive vector generated from the distance vector $\boldsymbol{D}(\boldsymbol{P}, \mathbf{O}) = (v_x, v_y, v_z)$

$$v(\boldsymbol{P}, \mathbf{O}) = \frac{V_{max}}{1 + e^{\|\boldsymbol{D}(\boldsymbol{P},\mathbf{O})\|(2/\rho)\alpha - \alpha}}$$

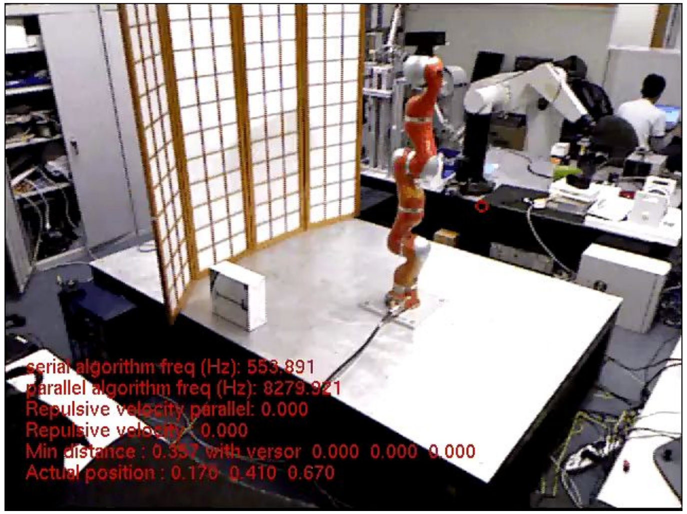


- repulsive vectors due to all obstacles near to point of interest are considered
  - orientation ⇒ sum of **all** repulsive vectors, magnitude ⇒ only due to **nearest** obstacle
  - inclusion of a pivoting strategy to avoid local minima or “too fast” obstacles



```
serial algorithm freq (Hz): 5065.904
parallel algorithm freq (Hz): 17456.595
Repulsive velocity parallel: 0.000
Repulsive velocity : 0.000
Min distance : 1000.000 with versor  0.000  0.000  0.000
Actual position : -0.100  0.450  0.740
```

video



```
serial algorithm freq (Hz): 553.891
parallel algorithm freq (Hz): 8279.921
Repulsive velocity parallel: 0.000
Repulsive velocity : 0.000
Min distance : 0.357 with versor  0.000  0.000  0.000
Actual position : 0.170  0.410  0.670
```

video

° = point of interest

— = minimum distance

— = repulsion due to min distance

— = repulsion due to all obstacles

Safe coexistence

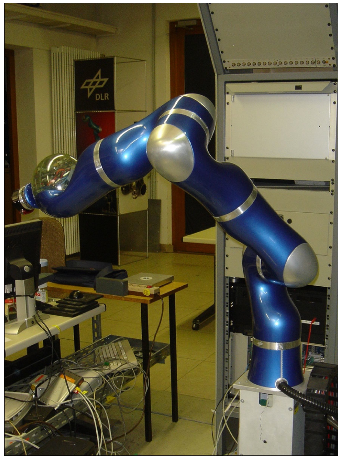
Collision avoidance in depth space (ICRA 2012)

Human and Robot share the same workspace...

video

What about using industrial robots?

From DLR LWR-III and KUKA LWR 4 to common industrial manipulators



KUKA **KR 5** Sixx R650

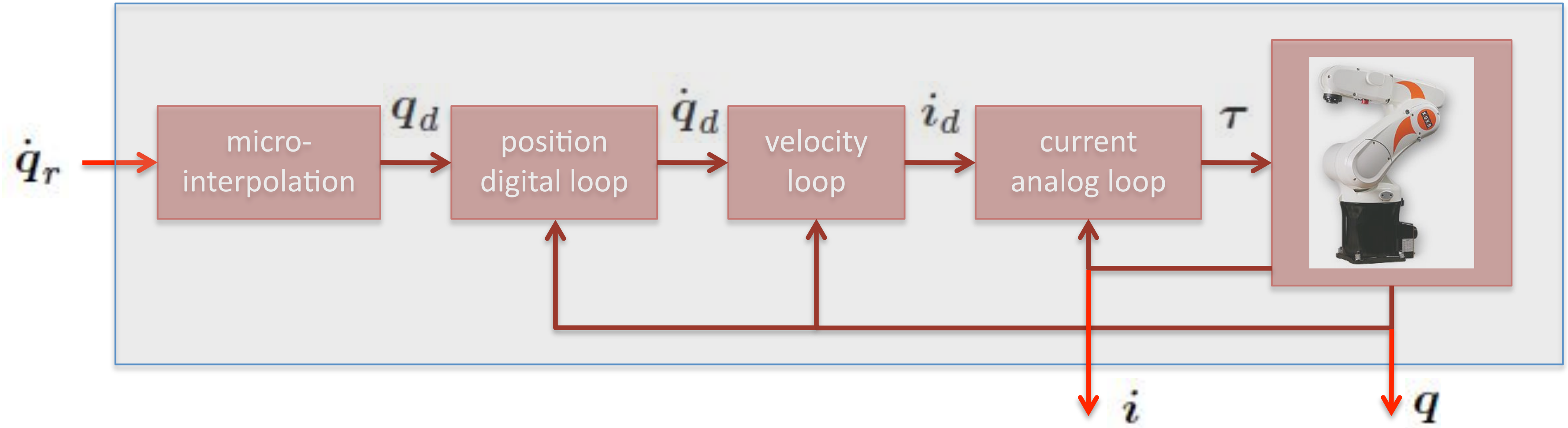
- 7-dof human-arm size, weight = 14 kg = payload
- dynamic model available
- joint torque sensor available
- torque controlled
- Fast Research Interface (FRI) @1 ms, with access to motor current commands

- 6-dof arm, weight = 28 kg, payload = 3 kg
- closed control architecture
- no information on dynamic model and on the industrial low-level controllers
- Robot Sensor Interface (RSI) @12 ms, for reading position encoders and (**absolute**) motor currents

- common aspects
  - can interface with MS Kinect and integrate Reflexxes Motion Libraries
  - user may develop middleware in ROS (operational nodes)

Closed control architecture

What can (or could) be done with the RSI

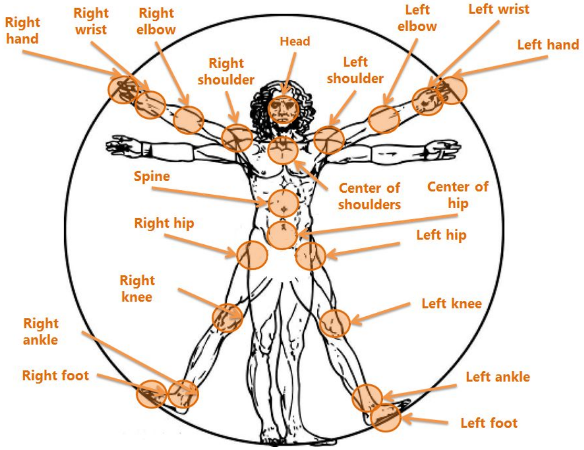


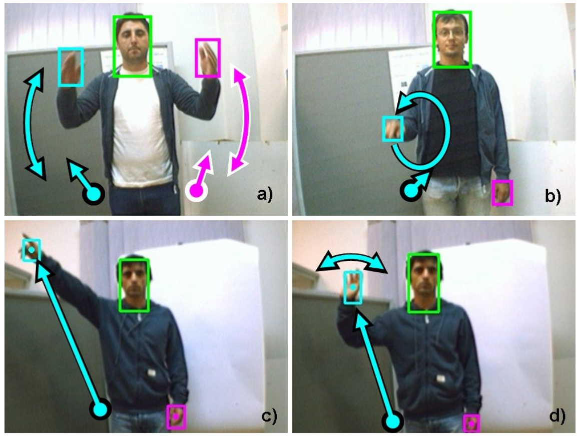
- the external reference velocity can be updated (but only every 12 ms), based on encoder and motor current readings + external sensor information
  - no torque or current command can be imposed by the user
  - no joint torque sensing available
  - no information on the dynamic model
  - no access to industrial low-level controllers
  - rely on "good" properties of the low-level (P/PD/PID) position controllers

Contactless collaboration

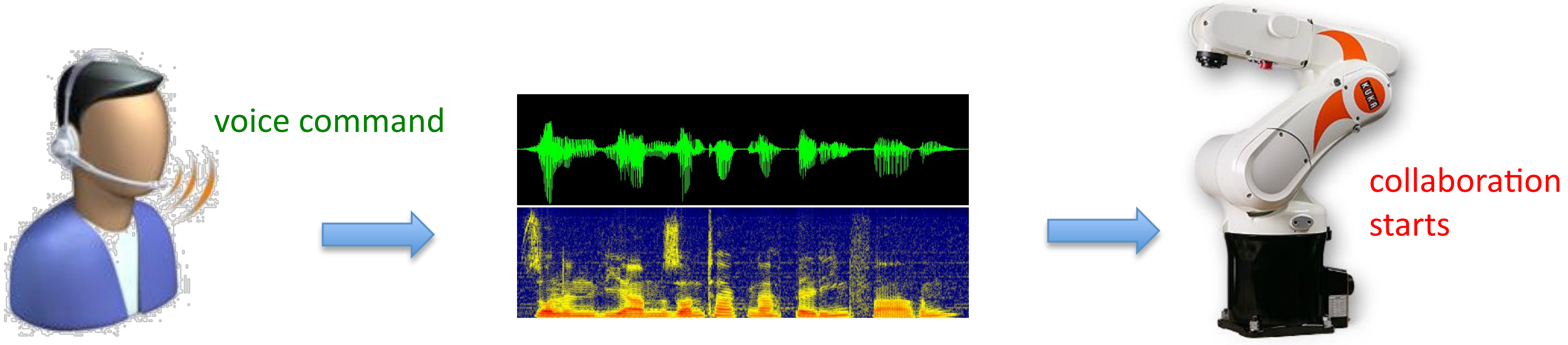
Using gesture and voice commands

- human body parts and gesture recognition





- speech recognition



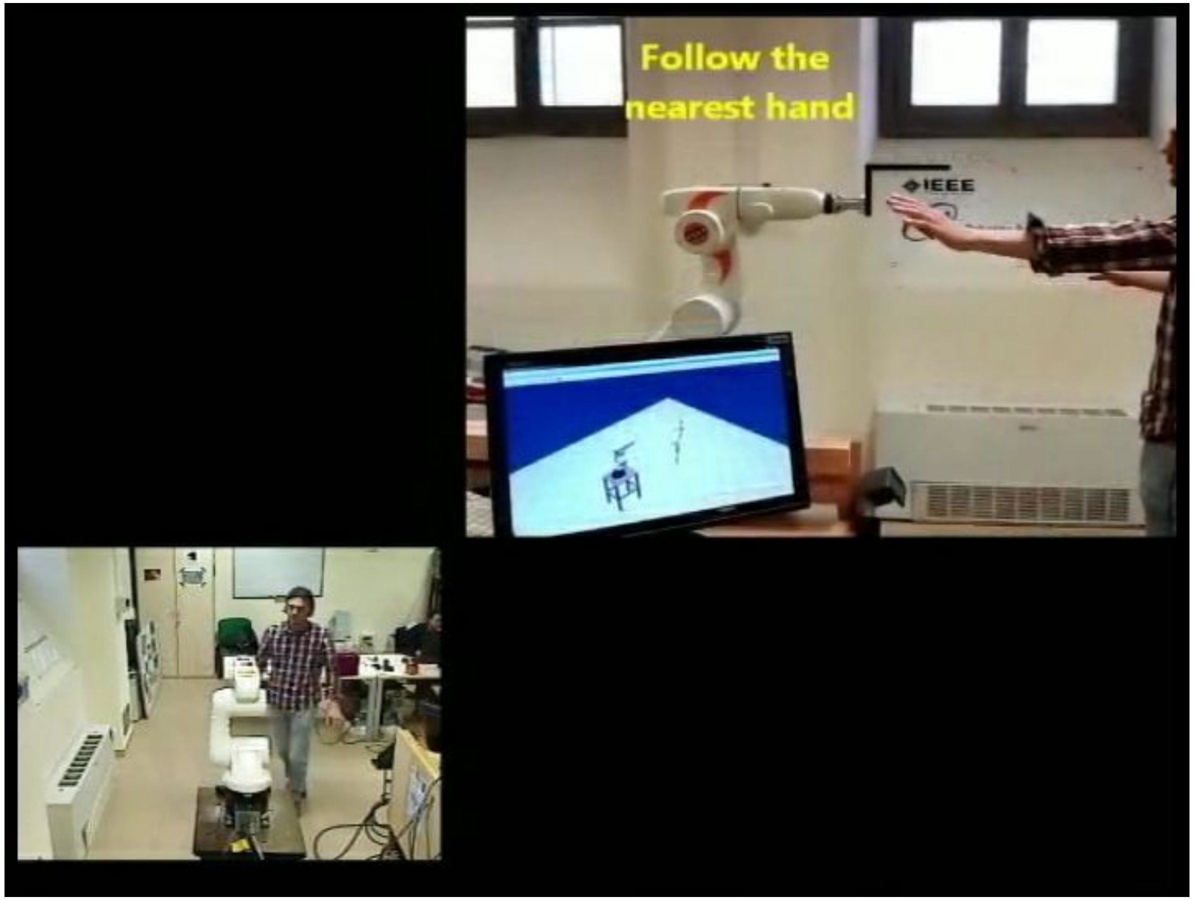
voice command

collaboration starts

Human-robot communication

Using MS Kinect and SDK library (Emanuele Magrini, 2012)

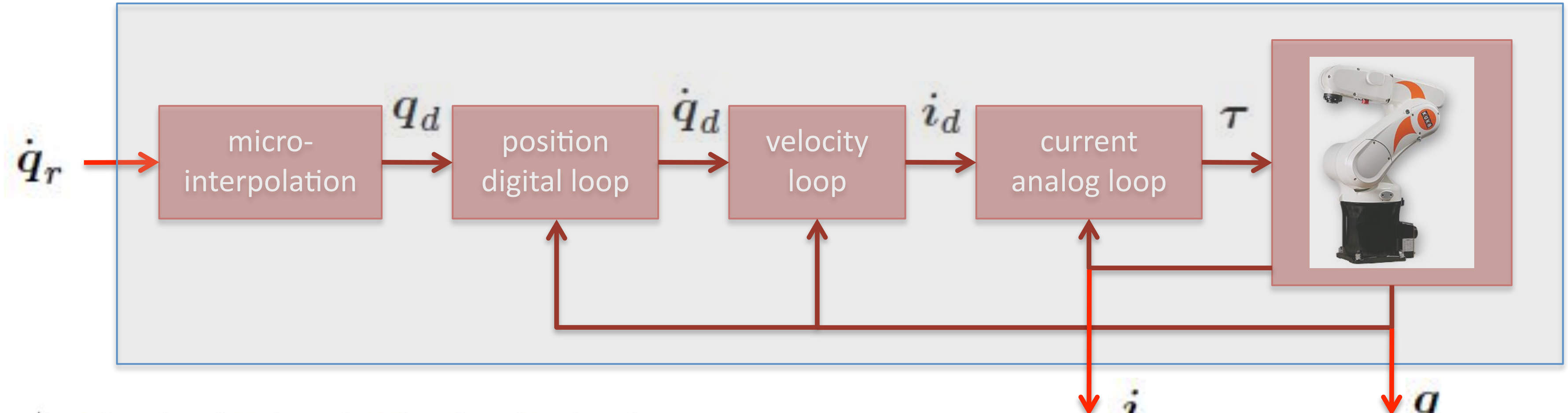
- the robot end-effector **position** is commanded by voice/gestures to **follow** (or **go to**) the human **left**, **right**, or **nearest** hand



video

Motor current signals

Suitable processing in real time



$\dot{q}_r$

micro-interpolation

q_d

position digital loop

$\dot{q}_d$

velocity loop

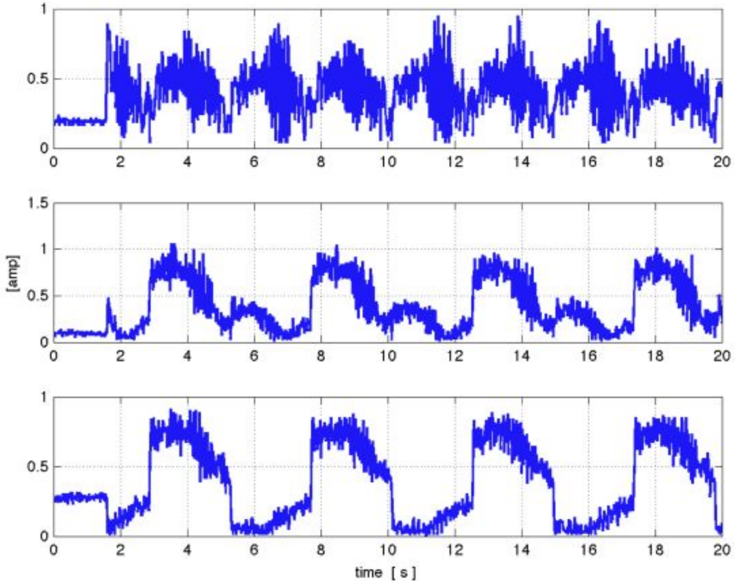
i_d

current analog loop

τ

i

q



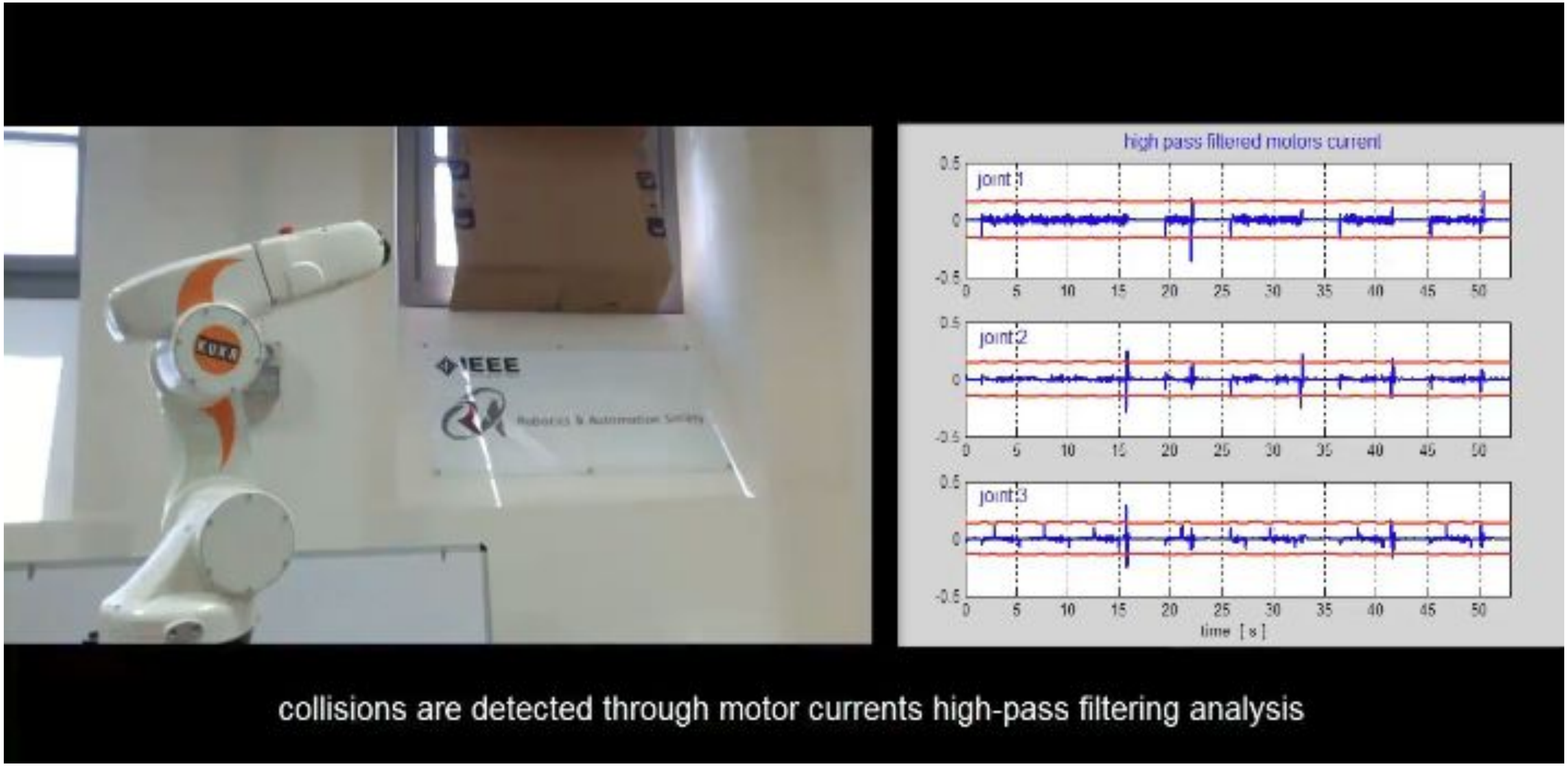
typical motor currents on the first three joints

- raw data are only/always positive values...
- processing to remove contribution due to gravity
- low-pass and high-pass digital filters are applied

Detect collision and stop

Simplest robot reaction strategy for safety

video



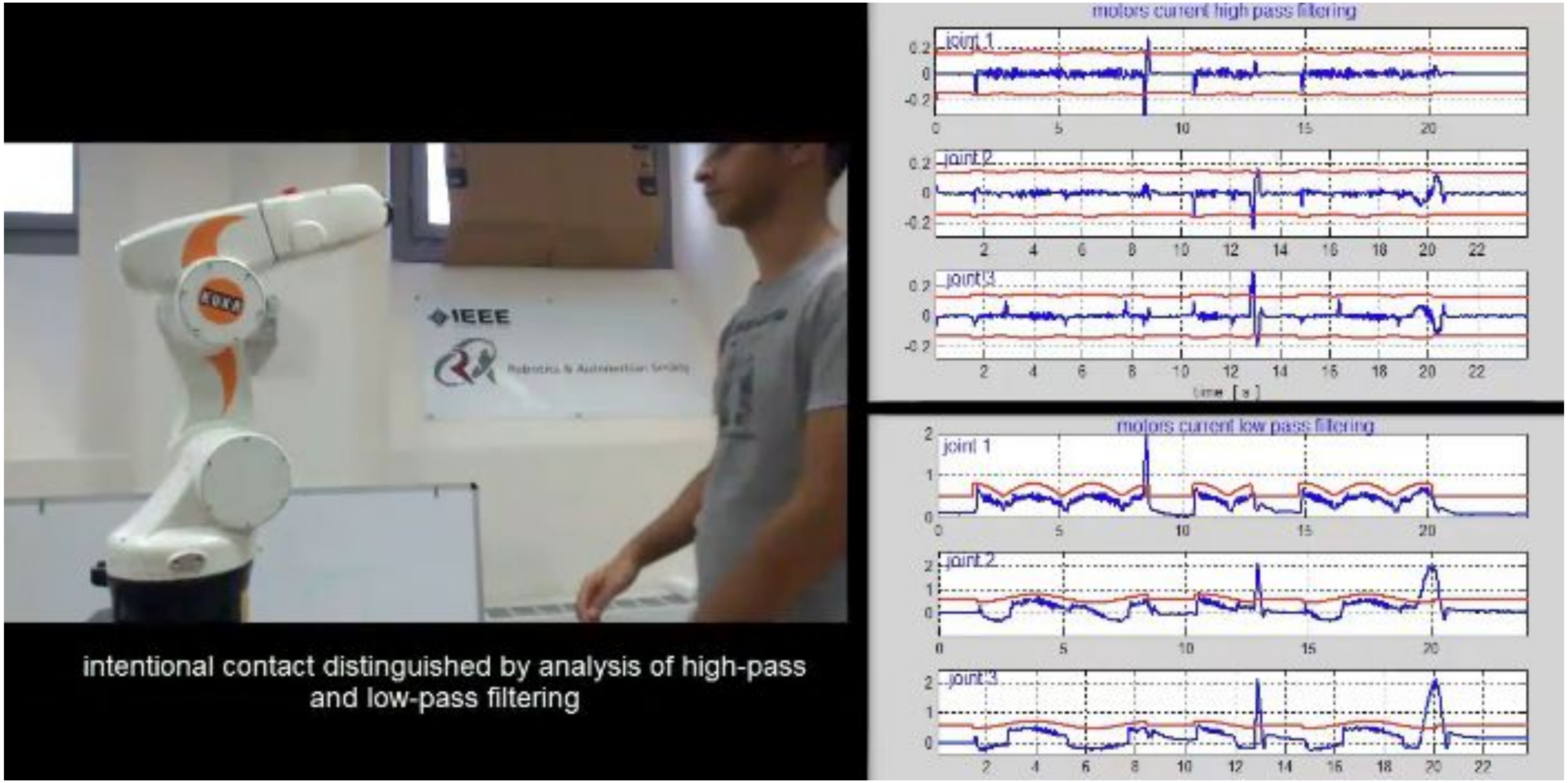
collisions are detected through motor currents high-pass filtering analysis

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

Distinguish hard and soft contacts

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

video



intentional contact distinguished by analysis of high-pass and low-pass filtering

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

Design robot reaction strategies

After collaboration mode has been established

pushing/pulling
the robot

still "cheating" with
the closed industrial
robot control architecture!

compliant-like
robot behavior

human pushes the robot away with a tiny force

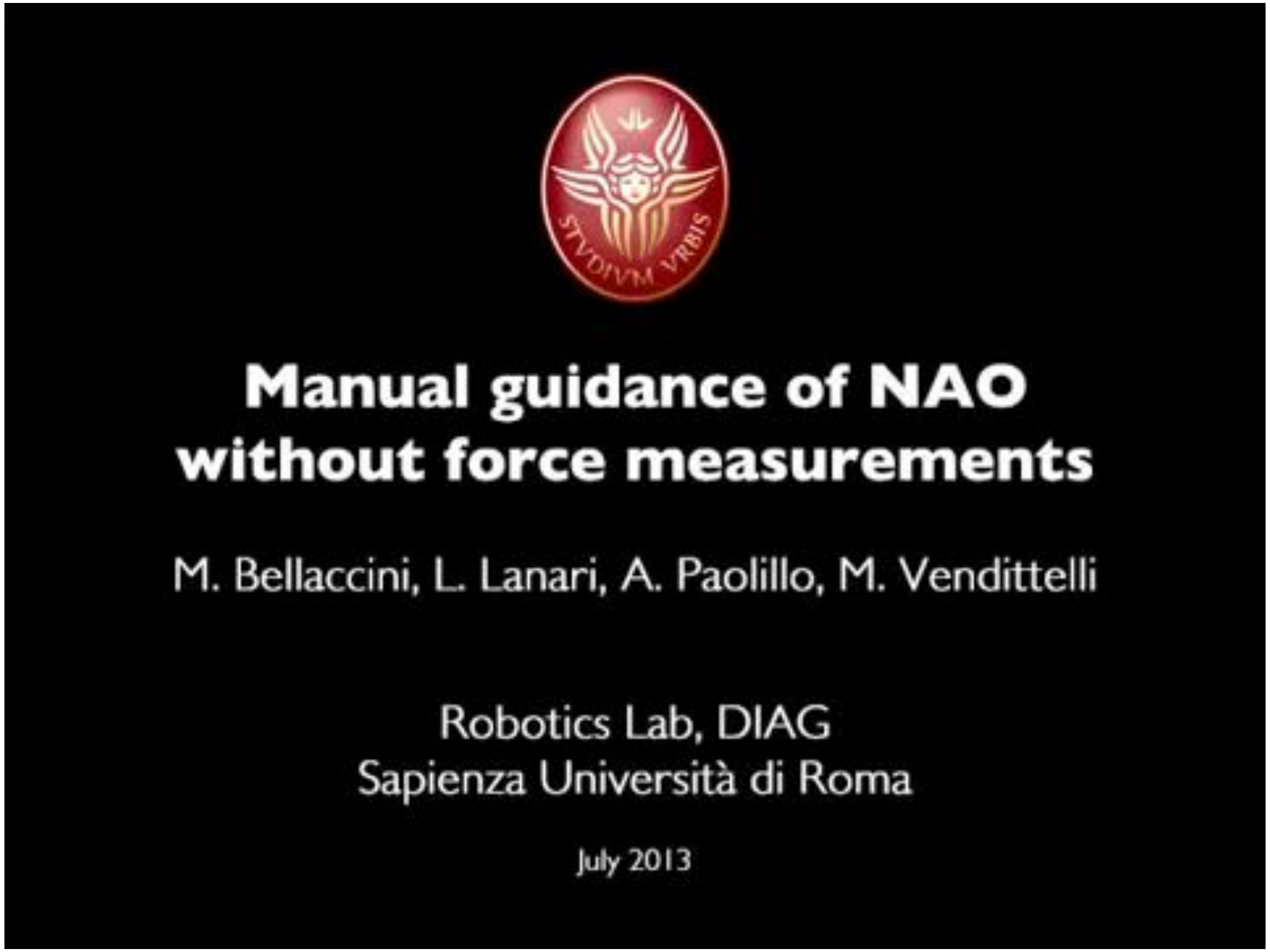
video

robot recovers initial configuration in a compliant way

video

Concept works also for commercial humanoids

Physical interaction with NAO without force sensing (ICRA 2014)



Manual guidance of NAO without force measurements

M. Bellaccini, L. Lanari, A. Paolillo, M. Vendittelli

Robotics Lab, DIAG
Sapienza Università di Roma

July 2013

video

Safe physical human-robot collaboration

IROS 2013 finalist for best video award

Safe Physical Human-Robot Collaboration

Fabrizio Flacco Alessandro De Luca

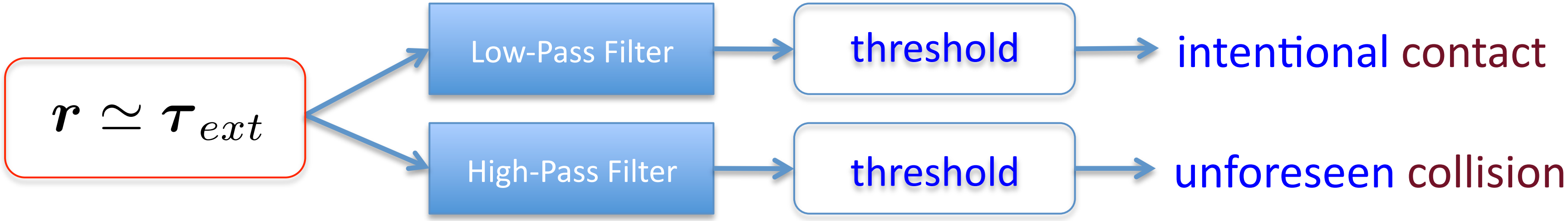
Robotics Lab, DIAG
Sapienza Università di Roma

March 2013

video

Collision or collaboration?

Distinguishing accidental collisions from intentional contacts on LWR 4



$$\boldsymbol{r} \simeq \boldsymbol{\tau}_{ext}$$

Low-Pass Filter → threshold → intentional contact

High-Pass Filter → threshold → unforeseen collision

- similarly to what done with motor currents on the KR5 and NAO robots, we can process the residuals of the LWR 4 robot in the frequency domain
- for intentional contacts, Kinect data are used to locate contact points (and then to do much more ...)

video @DIAG Robotics Lab, May 2014

Collaboration with force estimation

Combining internal and external sensing

- Task
  - identify in the least invasive way points on robot surface where contact occurs
  - 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 and to **estimate** the joint torques associated to the external contact force
  - use a depth sensor to **identify** the human parts in contact with the robot and **localize** the contact points on the robot structure
  - this approach can provide an estimate of external joint torque resulting from contact **forces**/**torques** applied (anywhere) to the robot

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

Estimation of contact force

Using the residual

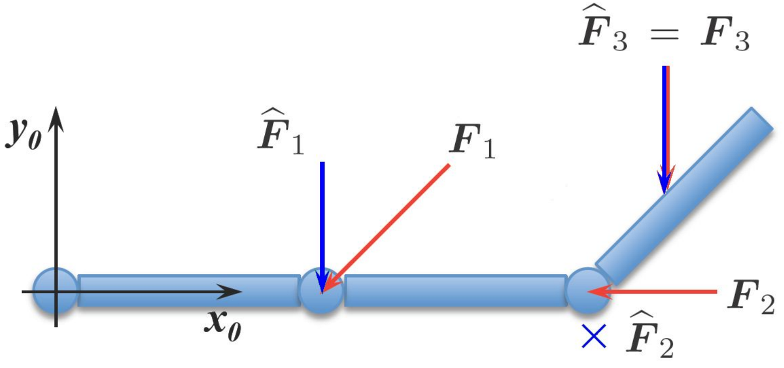
- most intentional contacts with a single hand can transfer only **negligible** torques
- to estimate reliably the **full** $\boldsymbol{\Gamma}_c$ we should have rank $\boldsymbol{J}_c = 6$
  - robot needs n ≥ 6 joints and contact should occur at a link i ≥ 6
- assume thus only **pure** Cartesian contact forces: $\boldsymbol{M}_c = \mathbf{0}$
- dimension of the contact force task is m = 3 and its **LS estimation** is

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

- **contact Jacobian** is needed ⇔ contact point, detected by external depth sensor
- **multiple** simultaneous contacts can be considered (e.g., the **two** human hands)

$$\begin{pmatrix} \widehat{\boldsymbol{F}}_1 \\ \widehat{\boldsymbol{F}}_2 \end{pmatrix} = \left(\boldsymbol{J}_{\boldsymbol{L}1}^T(\boldsymbol{q}) \;\; \boldsymbol{J}_{\boldsymbol{L}2}^T(\boldsymbol{q}) \right)^{\#}\boldsymbol{r}$$

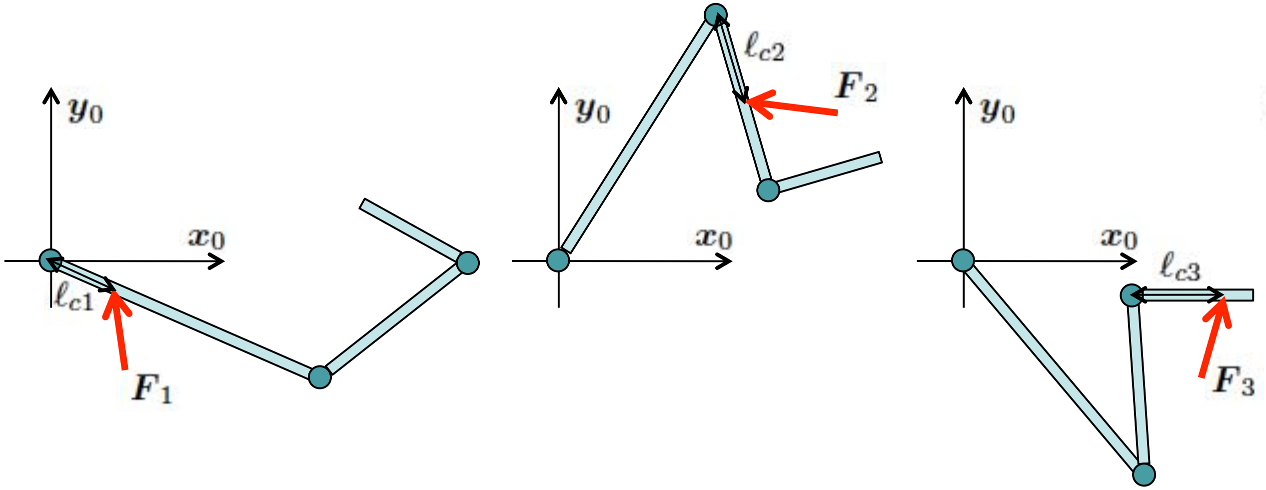
- **forces** $\boldsymbol{F}_c \in \mathcal{N}(\boldsymbol{J}_c^T(\boldsymbol{q}))$ will **not** be recovered (balanced by the robot structure, no effect on the residual)



Some analysis

What can we actually estimate? Is external sensing really needed?

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



r is a vector of dimension 3

rank $\{ J_{c1} \}$ = 1

rank $\{ J_{c2} \}$ = 2

rank $\{ J_{c3} \}$ = 2

$\boxed{\hat{F}_i}$ $\{$

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)

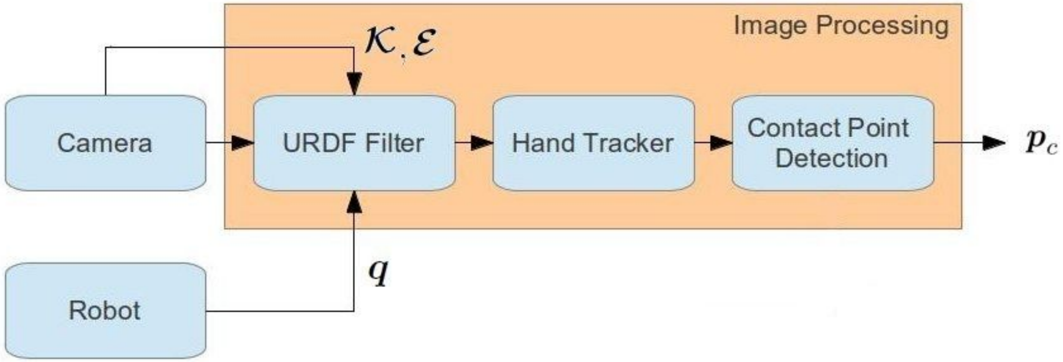
full force on link,
even not knowing contact
(**3** informative residuals)

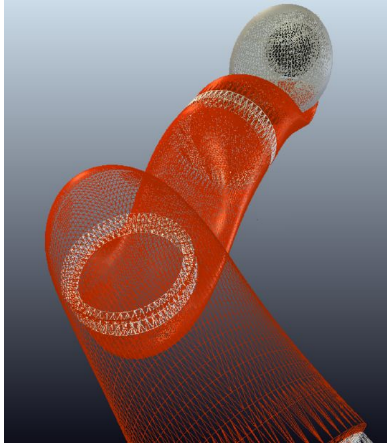
- forces $F_k \in \mathcal{N}(J_k^T(q))$ will not be recovered (even with known contact)

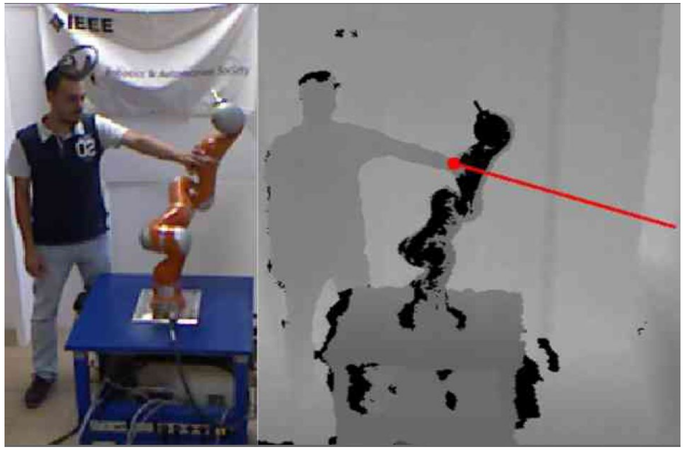
Distance and contact estimation

Using Kinect, CAD model, and residual to localize contact

- depth image is acquired by Kinect
- robot is removed from image (URDF filter by TUM)
- human hand tracking on filtered image
- 3D CAD model of robot and hand position are used to localize contact point on robot surface
- surfaces of robot links are modeled using polygonal patches
- 3D robot model is projected in workspace with a calibration matrix
- distances are computed between vertices of patches and the human hand
- when residual indicates a contact/collision (and the colliding link), the vertex with minimum distance is taken as contact point
- the algorithm is applied in parallel to both left and right hand





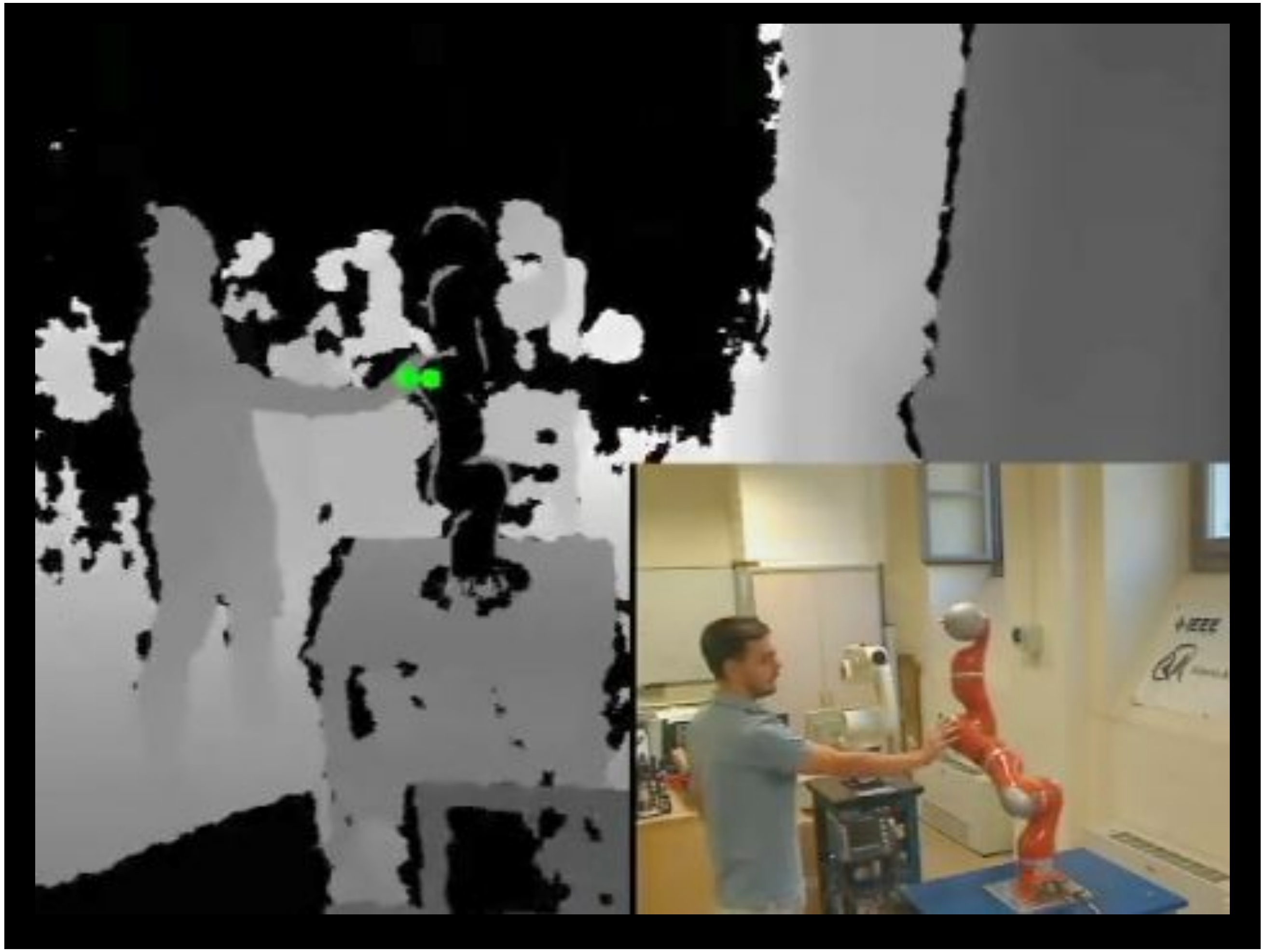


Distance and contact estimation

Range from about 20 cm down to 0 (contact), also for multiple locations

red =
left hand

green =
right hand



video

Validation of the “virtual” force sensor

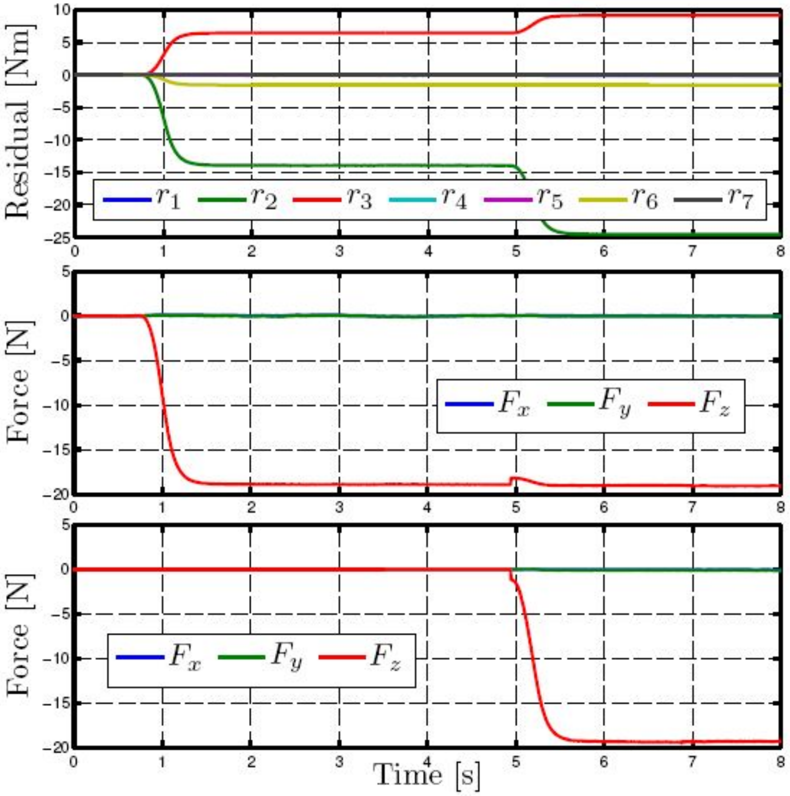
Experiments with a Kuka LWR 4

- Evaluation of estimated contact force
  - 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** contact

			using $\boldsymbol{J}_{\boldsymbol{L}c}$		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

Interaction control

How to use the estimate of the external contact force

- shaping the robot dynamic behavior in specific collaborative tasks
  - jointly carrying a load, holding a part in position, ... (whole arm **force** manipulation)
  - motion commanded in torque or **velocity** mode, implementing a force, impedance, or **admittance control** scheme **at the contact level**
- robot control using the estimated contact force
  - admittance control scheme is realized at the single (or first) contact point
  - desired **velocity** of contact point is assigned 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

  - the robot is redundant for contact tasks that occur on link i ≥ 4 (since m = 3), and an extra null-space motion contribution can then be added

$$\dot{\boldsymbol{q}} = \boldsymbol{J}_c^{\#}(\boldsymbol{q})\dot{\boldsymbol{p}}_c + \left(\boldsymbol{I} - \boldsymbol{J}_c^{\#}(\boldsymbol{q})\boldsymbol{J}_c(\boldsymbol{q})\right)\dot{\boldsymbol{q}}_0$$

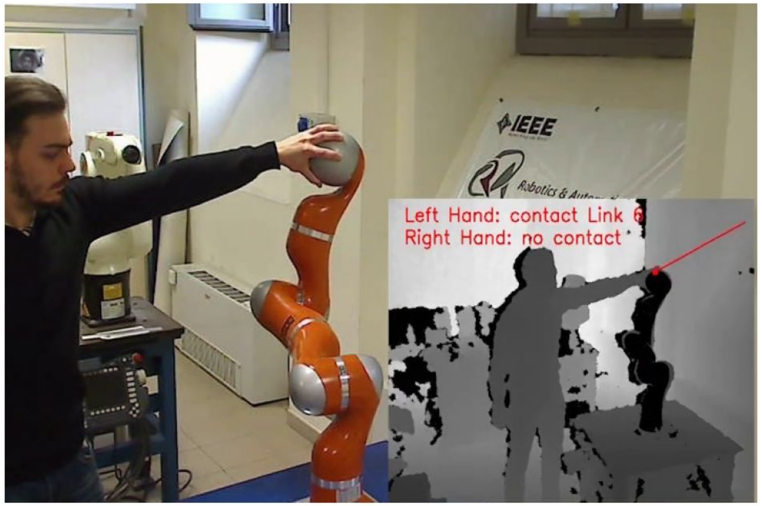
$$\dot{\boldsymbol{q}}_0 = \boldsymbol{K}_0(\boldsymbol{q}_d - \boldsymbol{q}), \qquad \boldsymbol{K}_0 = k_0 \boldsymbol{I} > 0$$

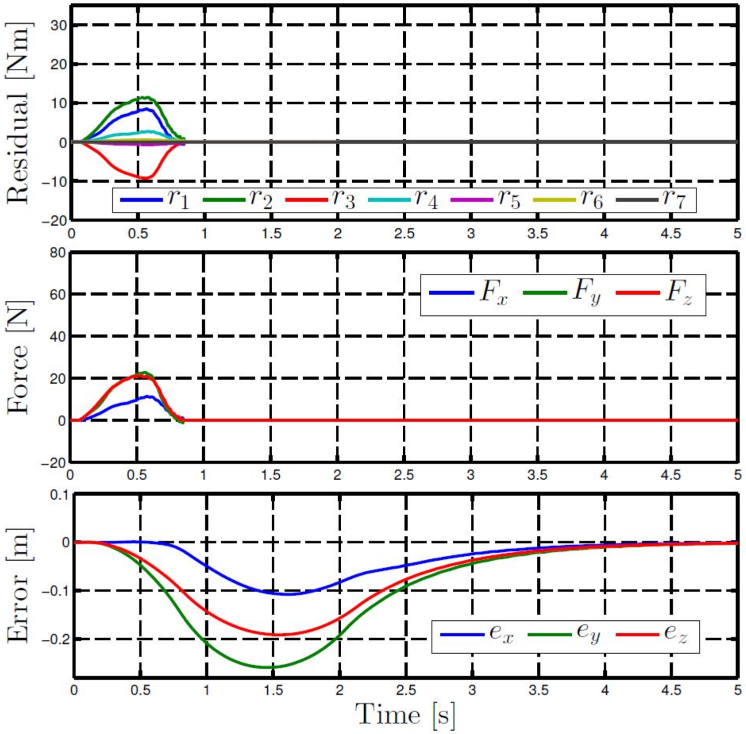
↖ initial robot configuration when interaction begins

pHRI control results

Soft behavior case

- control gain chosen to assign a **soft** behavior
- human pushes on robot link 6
- after detecting initial contact, the robot moves the contact point along the direction of the estimated force
- due to imposed **soft** behavior, the position error does still increase a bit even after losing contact





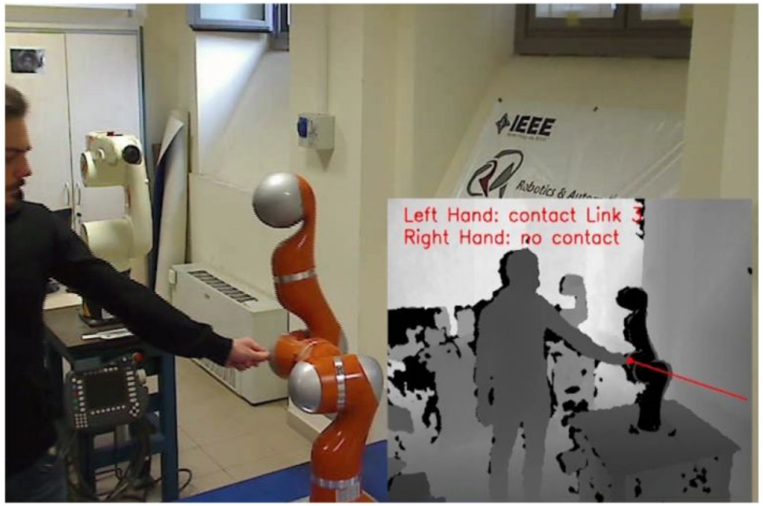
soft behavior case

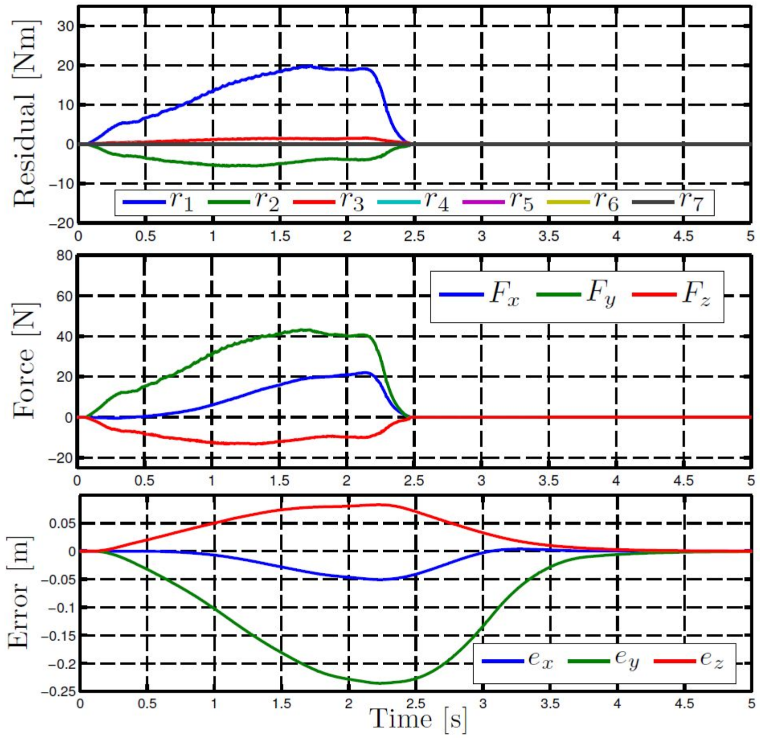
$k_a = 0.025 \quad k_p = 60 \quad k_0 = 0.6$

pHRI control results

Rigid behavior case

- control gain chosen to assign a **rigid** behavior
- human pushes on robot link 3
- due to the imposed **rigid** behavior, the force applied to move the robot is quite larger than before
- when the hand is removed, the contact returns smoothly to its position





rigid behavior case

$k_a = 0.01$ $k_p = 350$ $k_0 = 0.6$

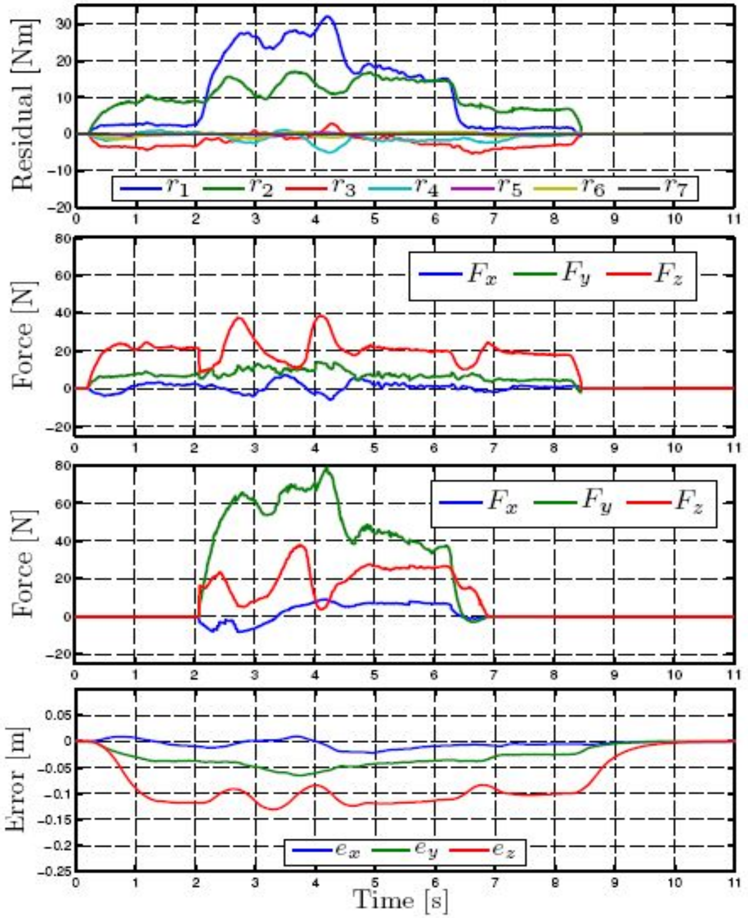
pHRI control results

Double contact case

- when a second contact occurs, a **task priority** strategy is adopted: contact closer to the robot base is considered as a secondary task
- its associated control command will be **projected** in the null space of the primary contact Jacobian

$$\dot{\boldsymbol{q}} = \boldsymbol{J}_1^{\#}(\boldsymbol{q})\,\boldsymbol{K}_1\Big(\widehat{\boldsymbol{F}}_1 + \boldsymbol{K}_p(\boldsymbol{p}_{1d} - \boldsymbol{p}_1)\Big) + \Big(\boldsymbol{I} - \boldsymbol{J}_1^{\#}(\boldsymbol{q})\boldsymbol{J}_1(\boldsymbol{q})\Big)\Big(\boldsymbol{J}_2^{\#}(\boldsymbol{q})\boldsymbol{K}_2\widehat{\boldsymbol{F}}_2 + \boldsymbol{K}_0(\boldsymbol{q}_{1d} - \boldsymbol{q})\Big)$$

- human pushes on robot link 6 (with left hand), then on link 3 (with right hand)



case of double contact

$k_a = 0.01$ $k_p = 350$ $k_0 = 0.6$ $k_2 = 0.03$

pHRI control results

IROS 2014

Estimation of Contact Forces using a Virtual Force Sensor

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Dipartimento di Ingegneria Informatica, Automatica e Gestionale, Sapienza Università di Roma

February 2014

video

Safe collaboration

Merging all together

External Forces

Contactless Collaboration

llaboration

Multiple Contact Points

Robot Co-worker

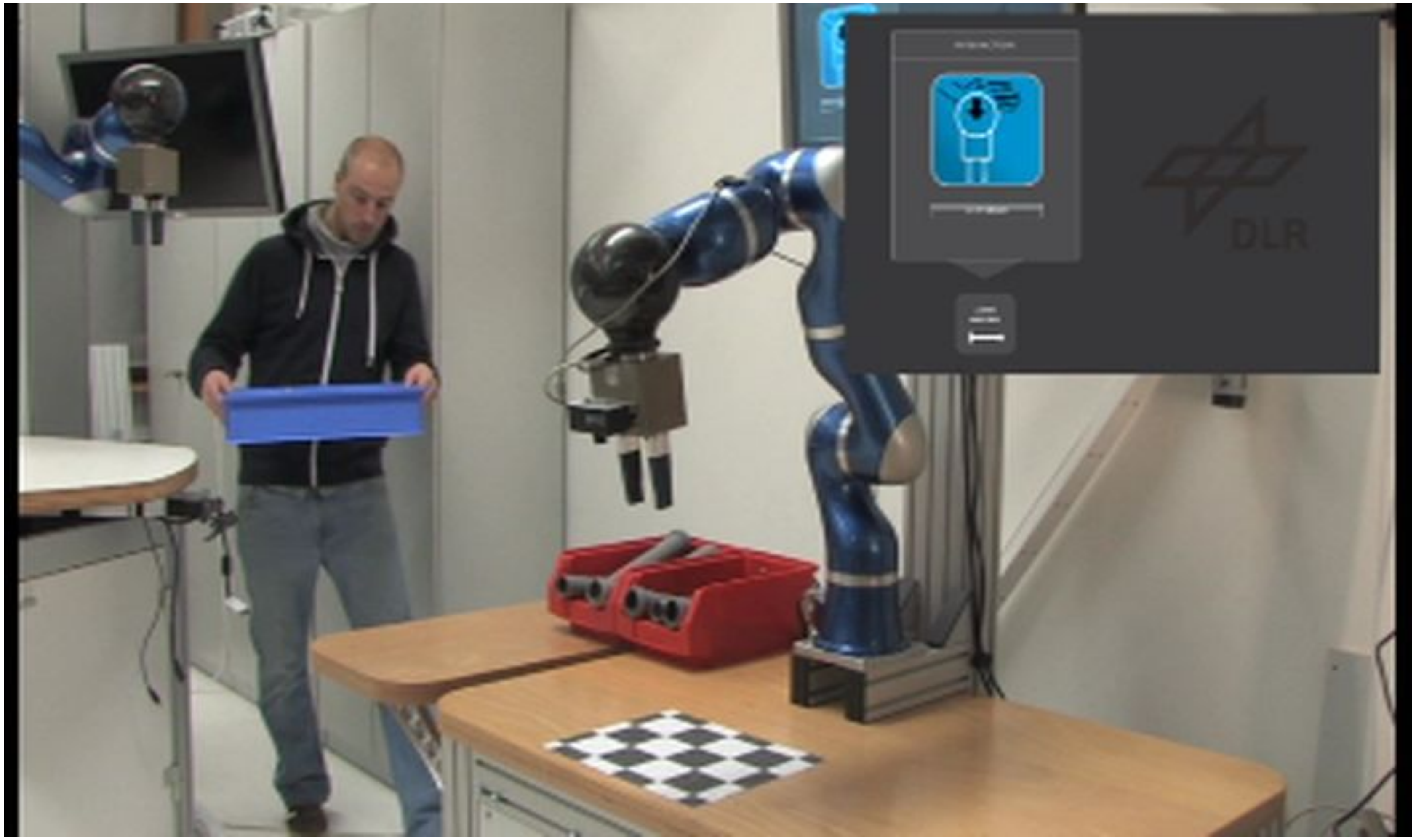
Collision Avoidance

Speech Recognition

Gesture Recognition

Robot co-worker at DLR

Physical HRI during task execution, with friendly user interface



video

Conclusion

Toward safe 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 (also using redundancy)
  - collision avoidance based on depth space data
  - estimation of contact force and location, by combining inner/outer sensing
  - force/impedance/admittance control, generalized at the contact level
  - exploit in any layer the presence of compliant joints (in next step, also with variable stiffness)

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- E. Magrini, F. Flacco, A. De Luca, "Estimation of contact force using a virtual force sensor," *IEEE/RSJ Int. Conf. on Intelligent Robots and System*, Chicago, September 2014 (**IROS 2014**)

Selected SAPHARI results

Summary video shown in the EU booth at ICRA 2013

Thanks and stay tuned!