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Recent Advances in physical Human-Robot Interaction

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SAPHARI
SAFE AND AUTONOMOUS PHYSICAL HUMAN-AWARE ROBOT INTERACTION

Keynote lecture
Roma, July 30, 2012

Motivation

Human-friendly robotics

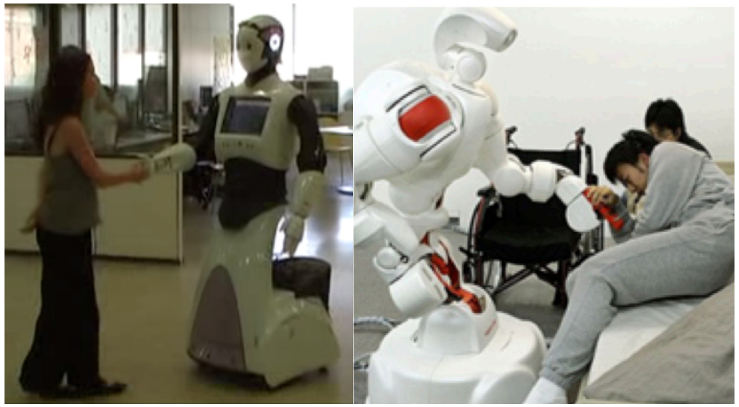
traditional robotics

replacing humans

co-workers on factory floor

human-friendly robotics

collaborating with humans

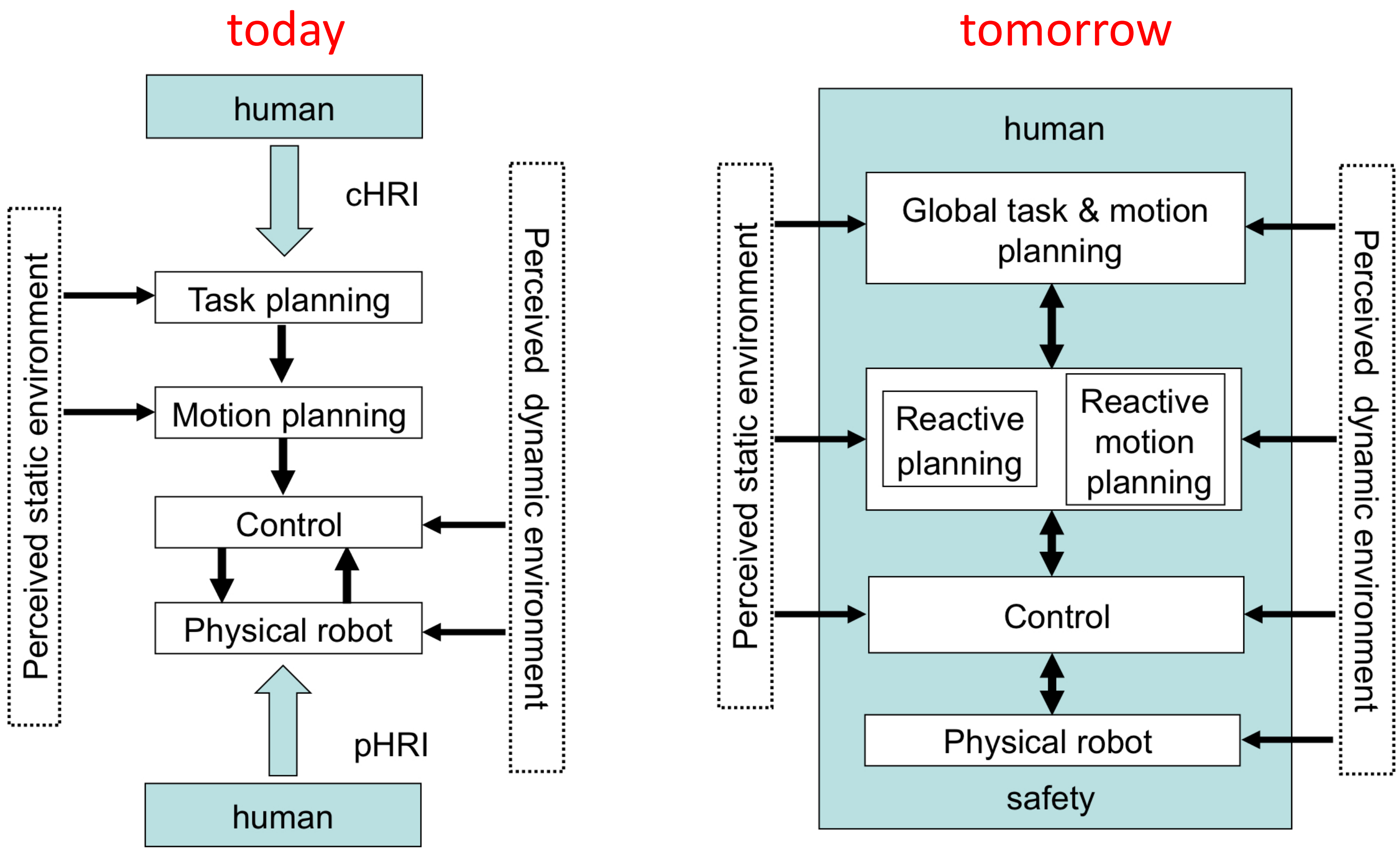


personal robots in service

Human-Robot Interaction

Need of revisiting robot control architectures

- **cognitive HRI**: bi-directional multi-modal communication and understanding
- **physical HRI**: exchange of contact forces, coordinated operation



Safe physical Human-Robot Interaction

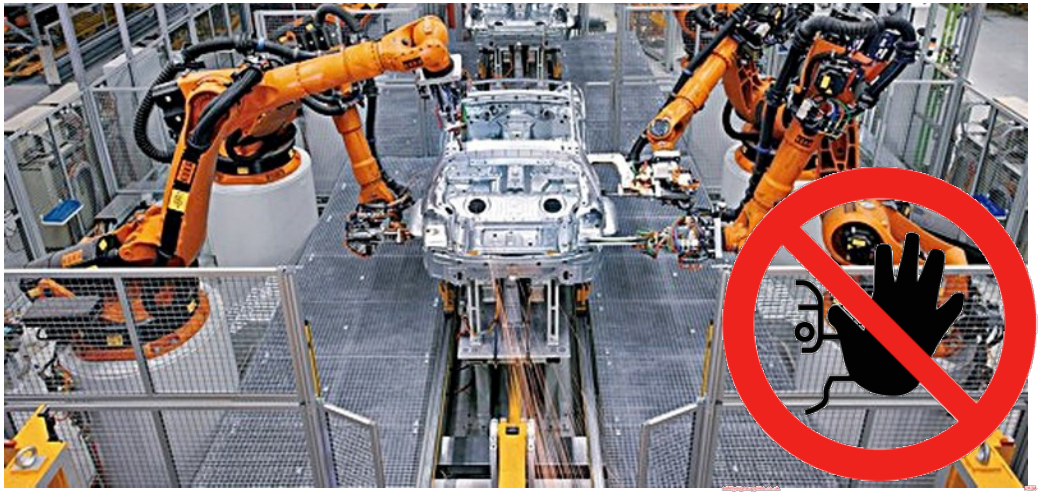
Hierarchy of consistent robot behaviors

- **integrated design and use** of mechanics, actuation, (proprio- and exteroceptive) sensing, communication, and control components

Safety

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

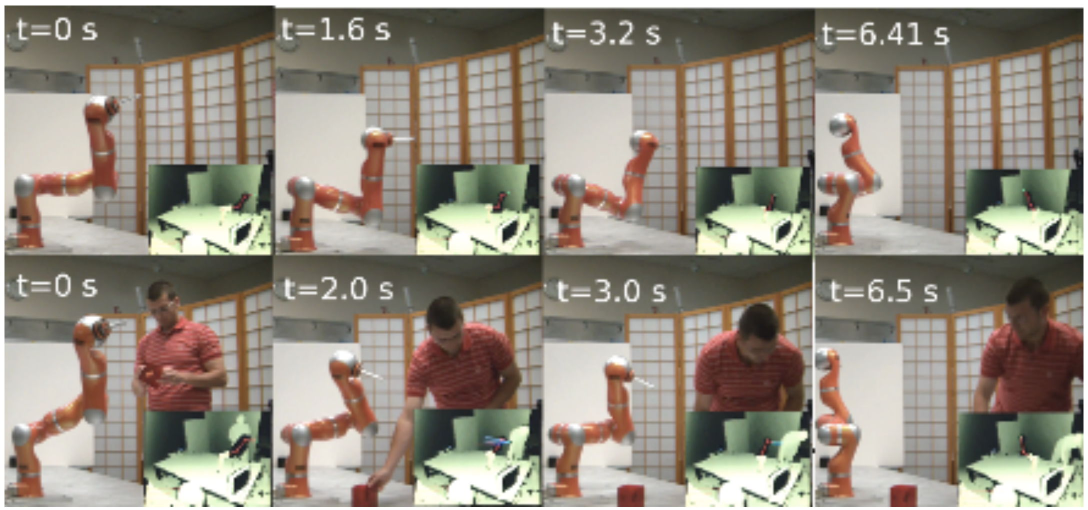
Classical solutions for preserving safety in industrial environments, i.e., using cages or stopping the robot in the presence of humans [**ISO 10218**], are inappropriate for pHRI



Hierarchy of consistent behaviors

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**)



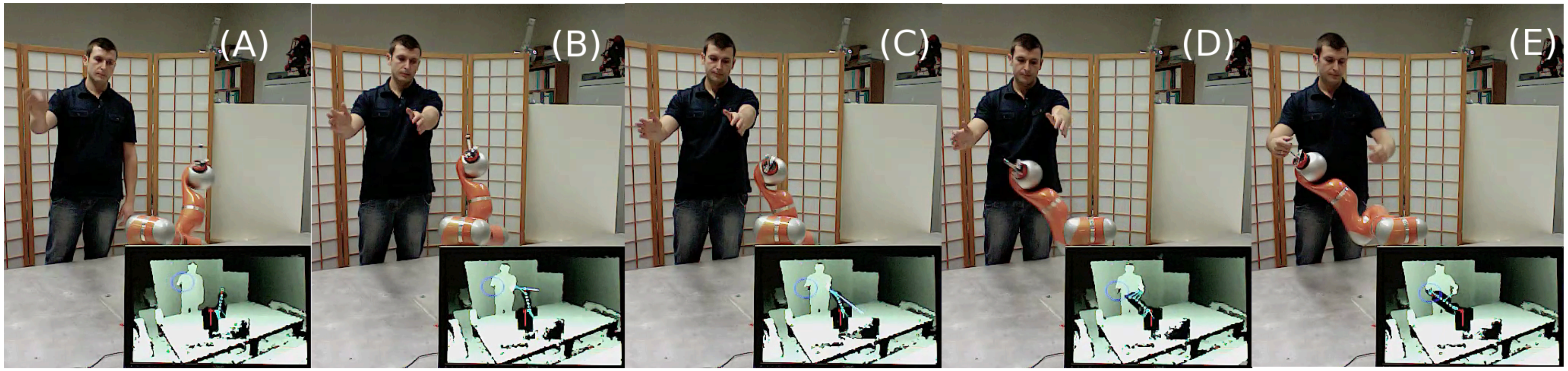
original robot task

safe HR coexistence

Physical HRI

Hierarchy of consistent behaviors

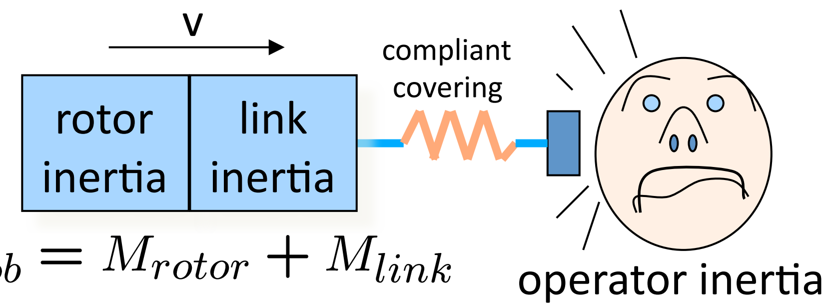
Collaboration occurs when the robot performs complex tasks with direct human interaction and coordination, in two modalities that are not mutually exclusive (contactless and physical)



Mechanics and Safety

A single-dof analysis: rigid joint (courtesy of A. Bicchi, Univ. Pisa)

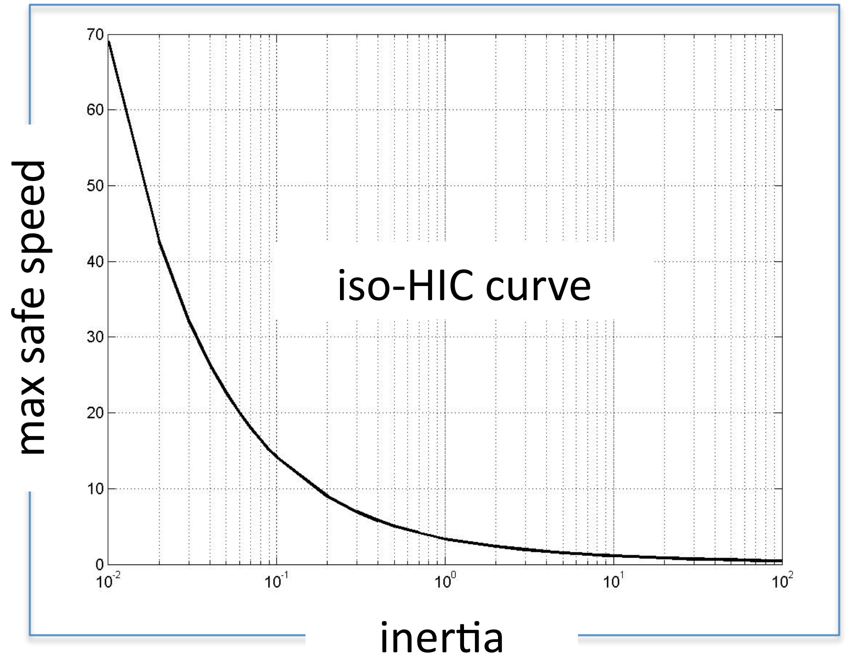
- "soft" robots or "soft" robot behavior is expected to reduce potential injuries due to unforeseen collisions with humans sharing the same workspace
- can we quantify this intuition?



$$M_{rob} = M_{rotor} + M_{link}$$

- HIC = Head Injury Criterion (used in automotive industry)

$$\text{HIC} = \frac{2^{\frac{5}{2}}\ M_{rob}^{\frac{7}{4}}\ K_{cov}^{\frac{3}{4}}}{\pi^{\frac{3}{2}}\ M_{ope}^{\frac{3}{4}}\ (M_{rob}+M_{ope})^{\frac{7}{4}}}\,|\text{v}|^{\frac{5}{2}}$$

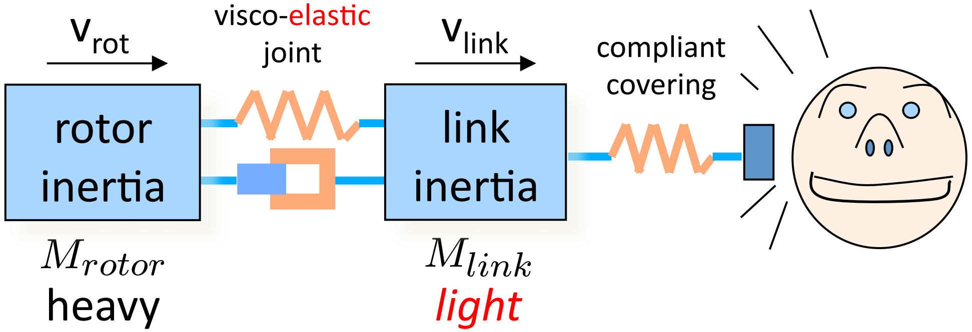


$$|v|_{max} = \beta(M_{ope}, M_{rob}, K_{cov})HIC_{max}^{\frac{2}{5}}$$

Mechanics and Safety

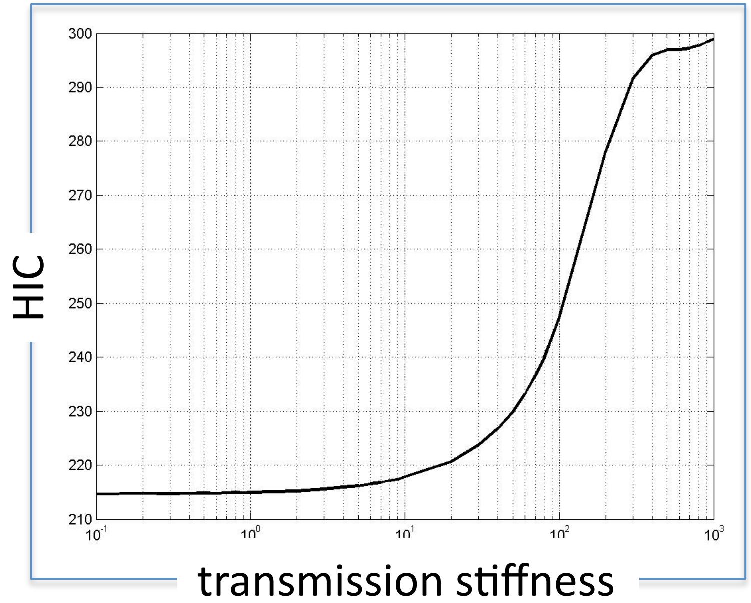
Compliant joint

- active force feedback from contact sensor is not enough to increase operating speed with rigid joint and safety constraint (limited control/sampling bandwidth)
- **basic idea**: decouple rotor from link inertia via passive compliant transmission (elastic joint) and reduce link inertia (lightweight manipulator)



WAM robot
(Salisbury 1988)

DLR LWR-III
(Hirzinger 2001)

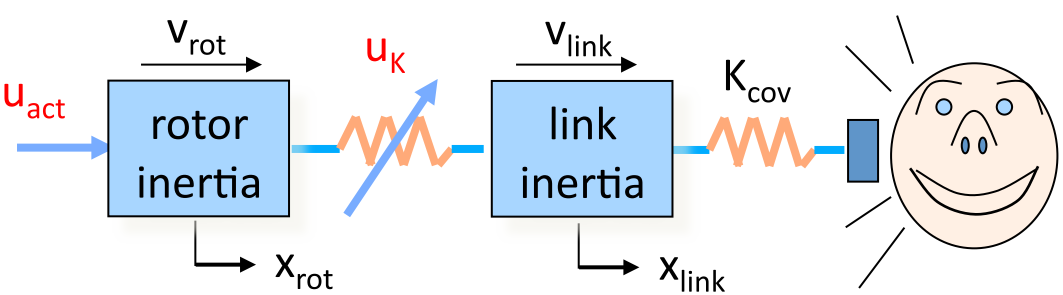


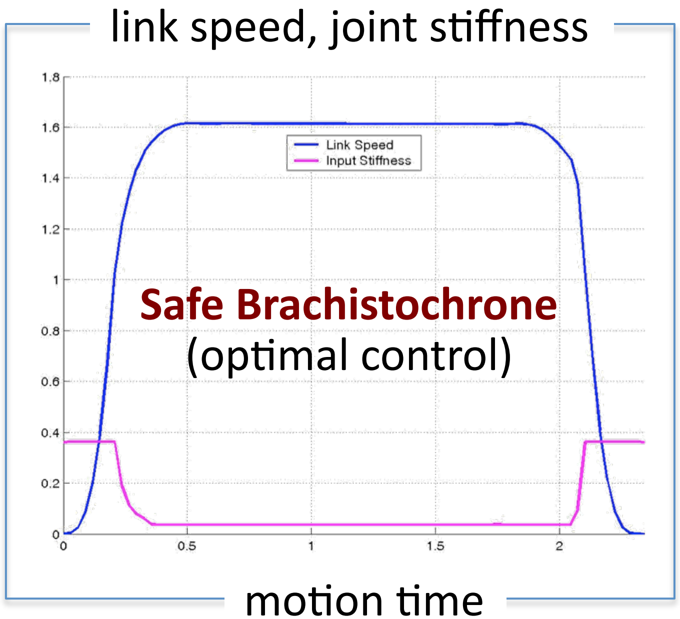
transmissions with joint elasticity:
Harmonic Drives, cables, tendons, ...

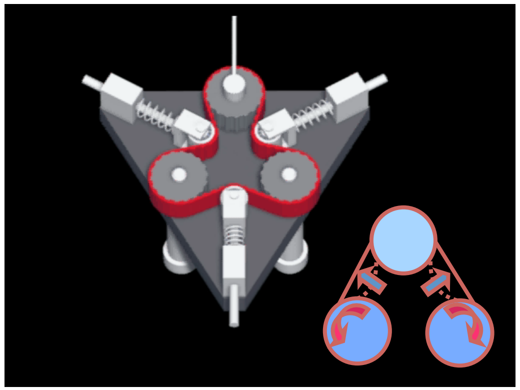
Mechanics and Safety

Variable Stiffness Actuation (VSA)

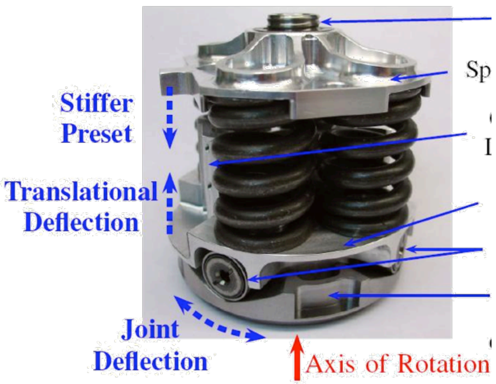
- low joint stiffness ⇒ slow response; high stiffness ⇒ high reflected inertia
  limited safe speed under safety constraint (limited control/sampling bandwidth)
- **idea**: a second motor to modify on line the nonlinear stiffness of transmissions







UniPisa VSA-I
antagonistic device (2005)



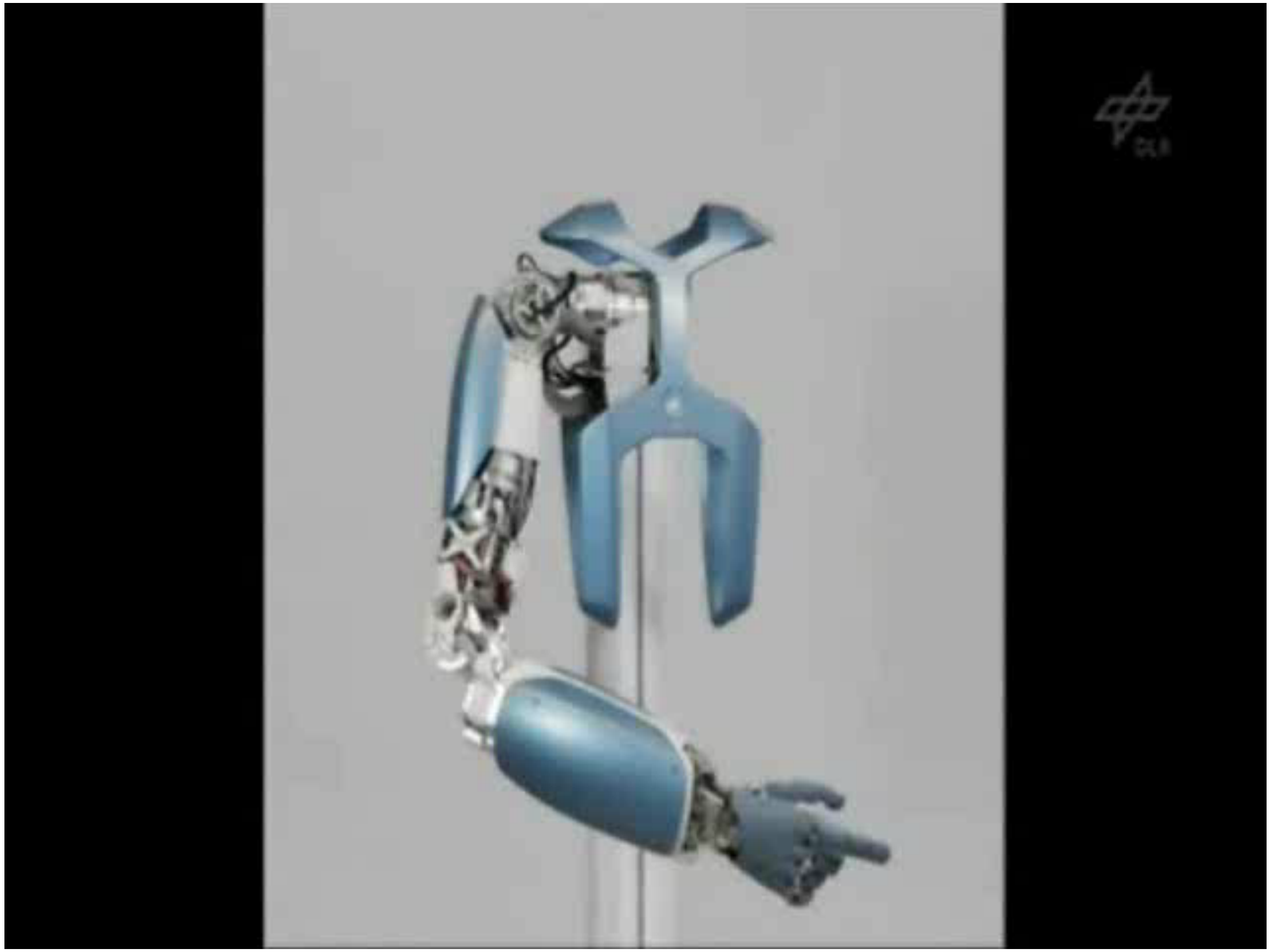
DLR VSJ
serial device (2009)

... and, more recently, even many more!

VSA-based multi-dof robot

DLR hand and upper torso in hammering task

- not only **safety**, but also **efficient use of energy**



Summarizing

Mechanical design and control

- co-design techniques of mechanics and control for safe, yet fast, strong, and accurate robot arms
- use of constant or variable stiffness joints are viable solutions, complemented by lightweight materials for the robot links
- new paradigm: “design for safety, control for performance”
- **Q:** can all robots with nonlinear flexible transmissions and multi-body dynamics be controlled so as to behave as “rigid” & “independent single-dofs systems”? *(at least, during free motion)*
- YES! Using feedback linearization (nonlinear feedback law, based on measures of the robot state)
- what happens when (intended) contacts or (unexpected) collisions occur?
- can a control design help in keeping a safe behavior? if so, how?

Safe collision handling

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 **always 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

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

inertia matrix

Coriolis/centrifugal terms

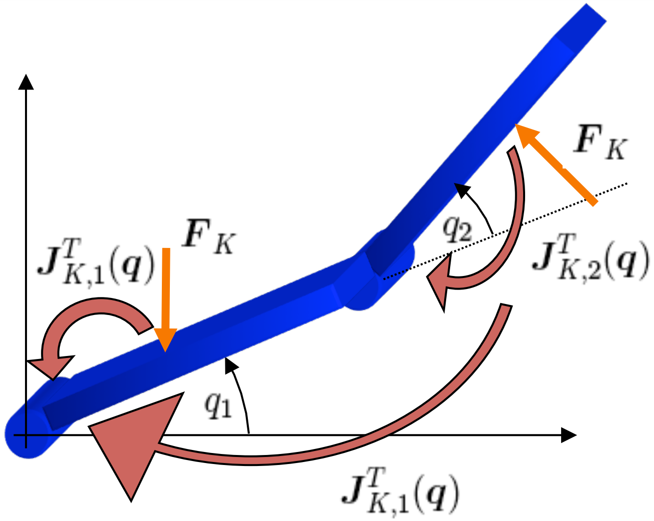
joint torque due to link collision

transpose of the Jacobian associated to the contact point

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

Collision detection and isolation

Method based on **residual** vector for robots with **rigid** joints



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

residual vector monitors the robot generalized momentum $p = M(q)\dot{q}$

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

$K_I > 0$ (diagonal)

each component of r is a decoupled, first-order, unity-gain filtered version of the unknown external torque

$\dot{r} = -K_I r + K_I \tau_K$ ➡ $K_I \to \infty$ ➡ $r \approx \tau_K$ **detection** (over a threshold)

collision at link i ➡ $r = [* \quad \dots \quad * \quad * \quad 0 \quad \dots \quad 0]^T$ **isolation**

i+1 ... N

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

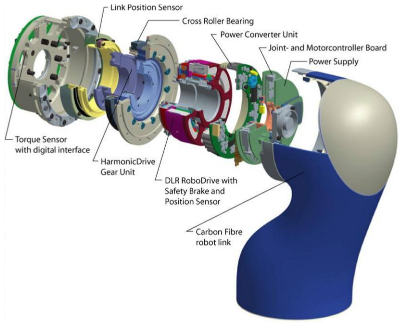
$$B\ddot{\theta} + \tau_J = \tau$$

← 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



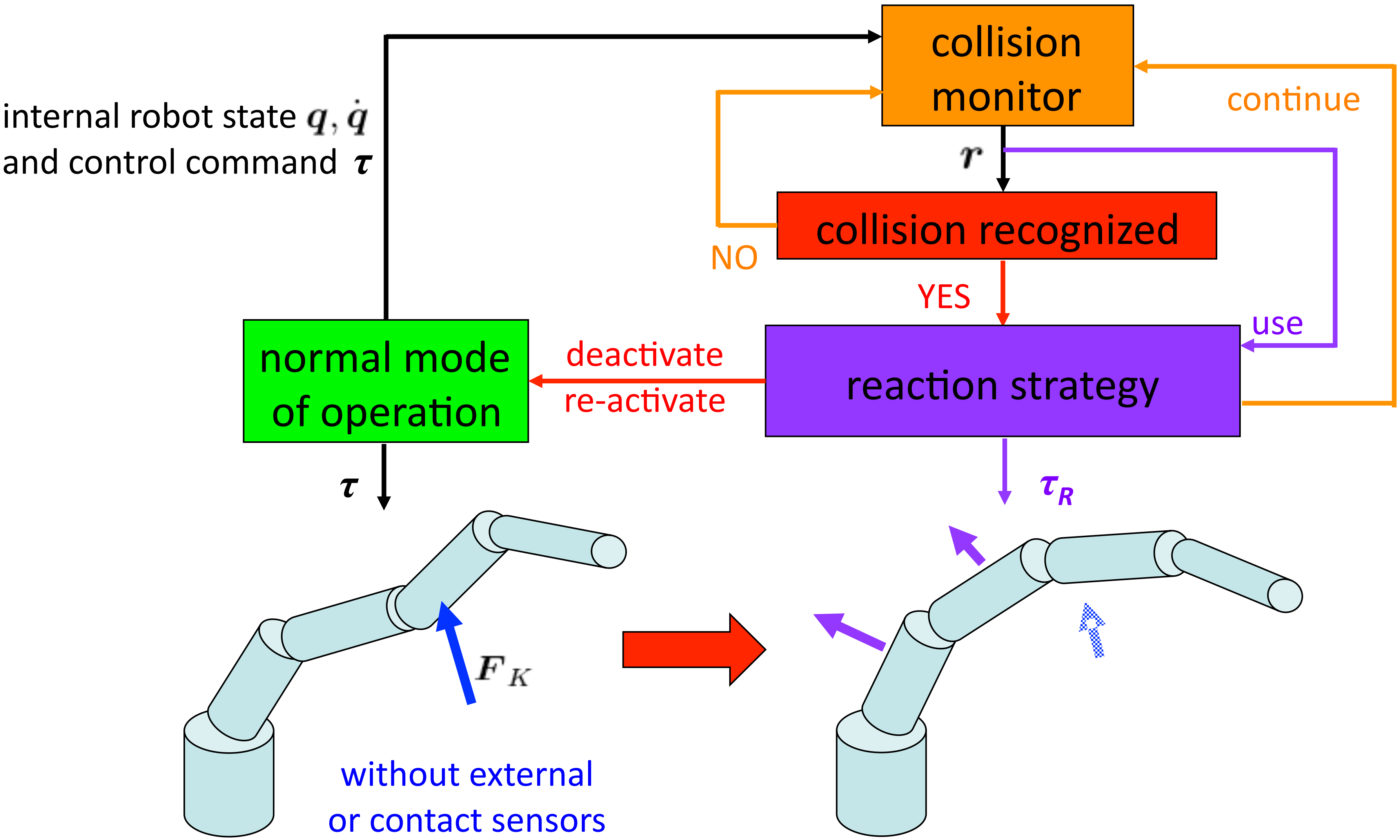
$$\boxed{\tau \rightarrow \tau_J}$$

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

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

Collision reaction

Method based on residuals



Collision detection and reaction

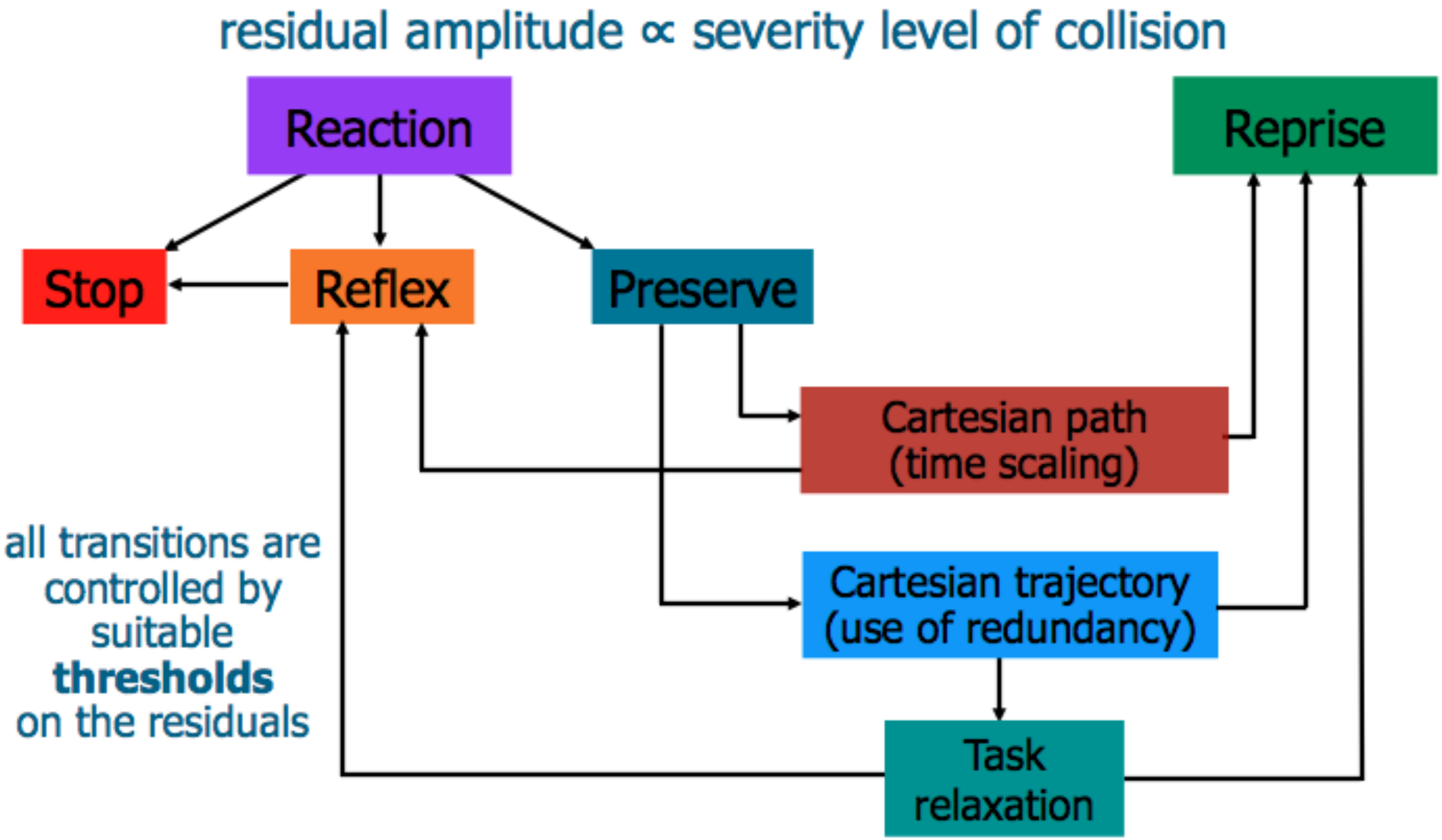
Residual-based experiments on DLR LWR-III

- collision detection followed by different reaction strategies
- detection time: 1-2 ms, reaction time: + 1 ms

admittance mode	reflex torque	reflex torque
first impact at 60°/s		first impact at 90°/s
$\dot{\boldsymbol{q}}_r = \boldsymbol{K}_Q \boldsymbol{r}$	$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q})\left(\boldsymbol{K}_R \boldsymbol{r} - \boldsymbol{D}_R \dot{\boldsymbol{q}}\right) + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{r}$	

Collision reaction

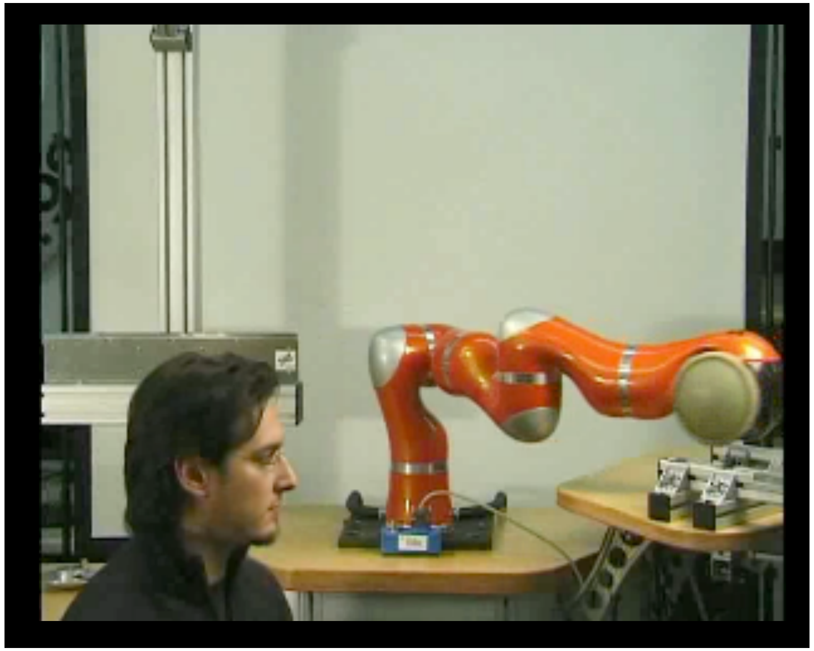
Portfolio of possible robot reactions



Collision reaction

Further examples

- without external sensing & no strict need of joint torque measurements
- any place, any time ...

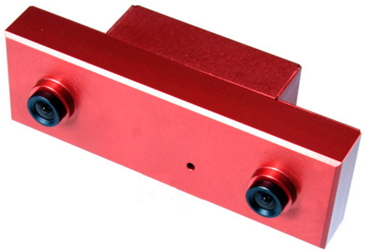


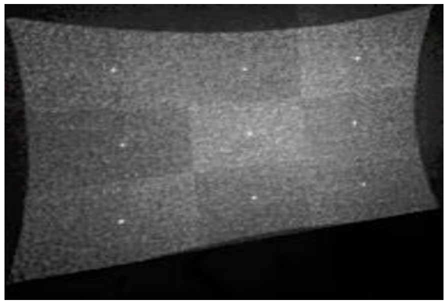
results from PHRIENDS project
(and thanks to DLR volunteer Sami Haddadin!)

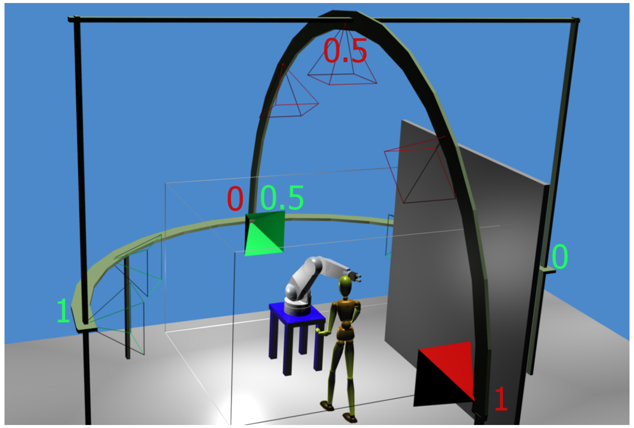
Collision avoidance

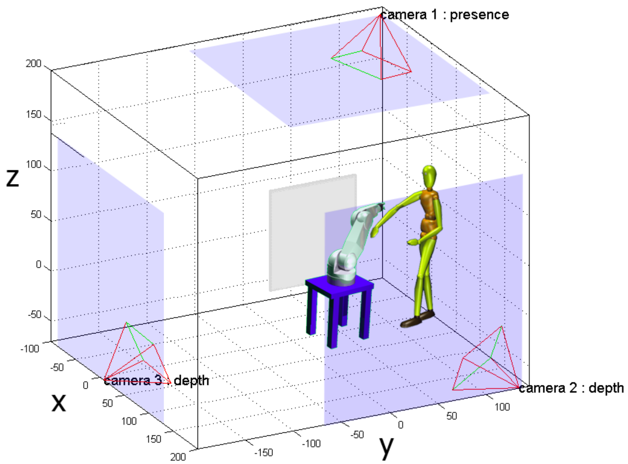
Using exteroceptive sensors to monitor robot workspace

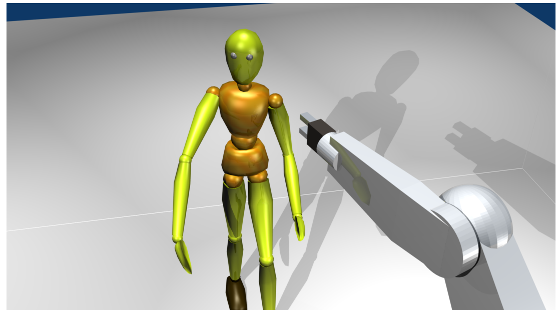
- external sensing: stereo-camera, TOF, structured light, depth, laser, presence, ...
  placed optimally to minimize occlusions (robot can be removed from images)

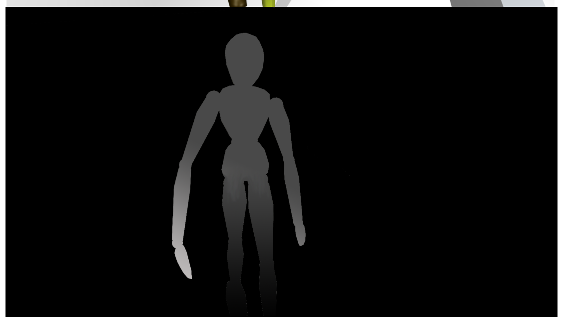


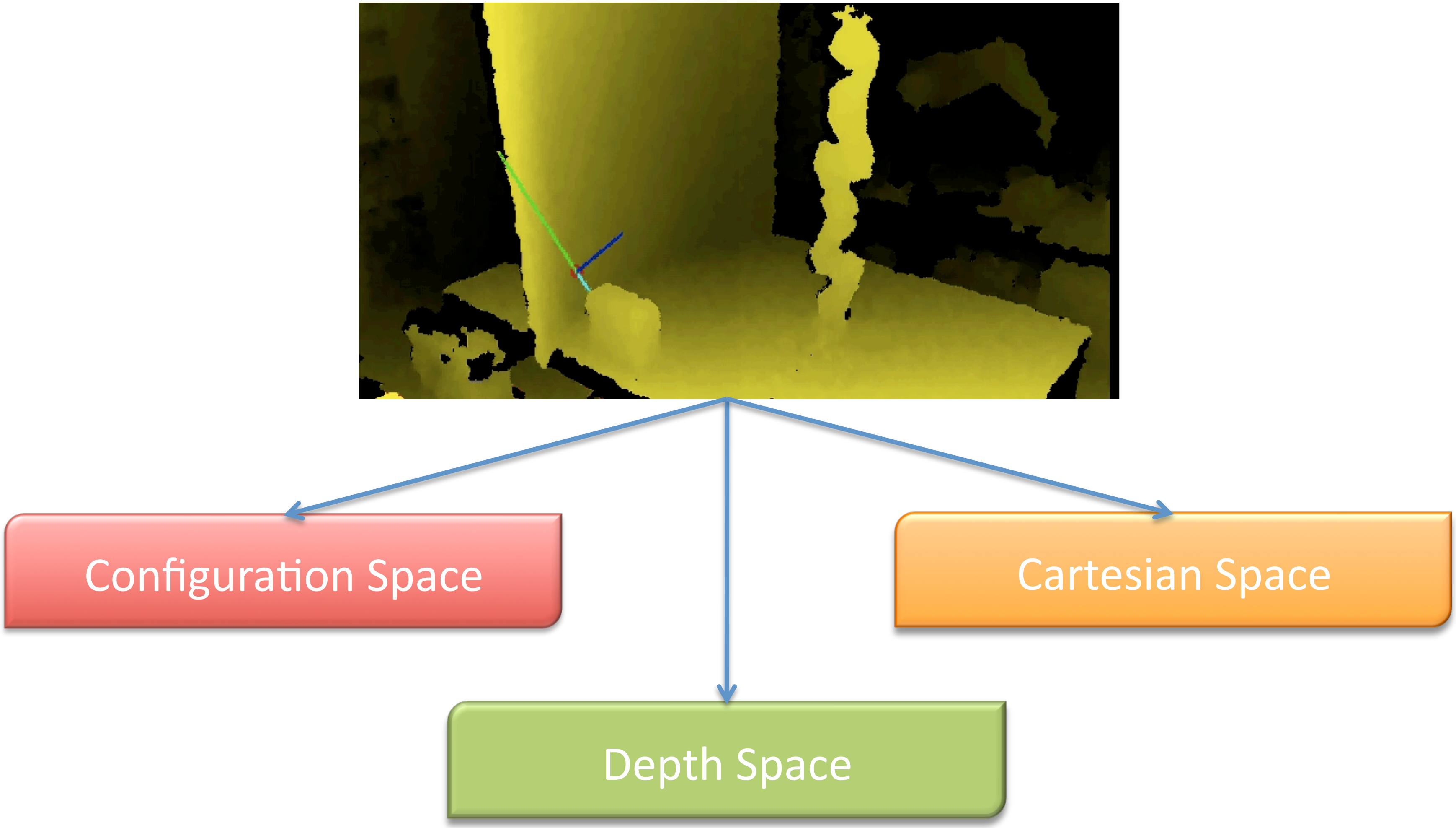












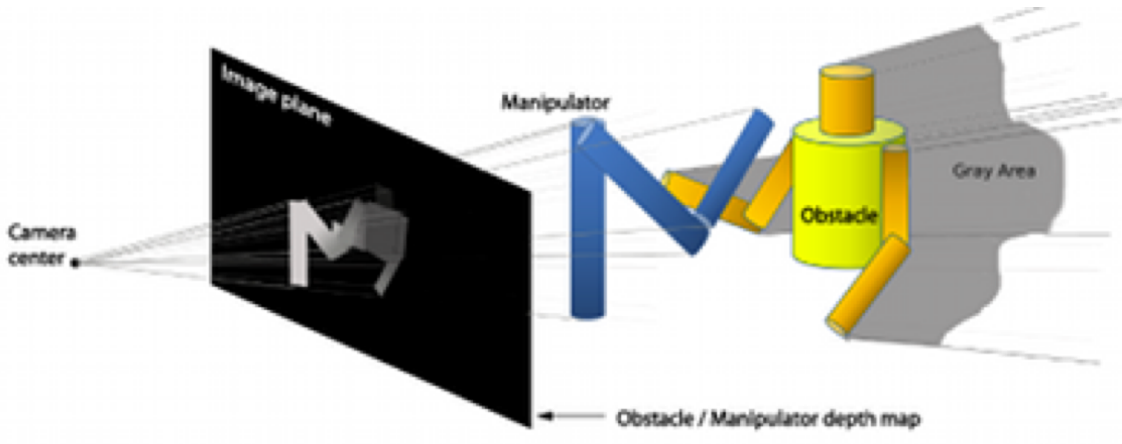
Configuration Space
Cartesian Space
Depth Space

- 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

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

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

$$d_p = z_C$$



Depth space

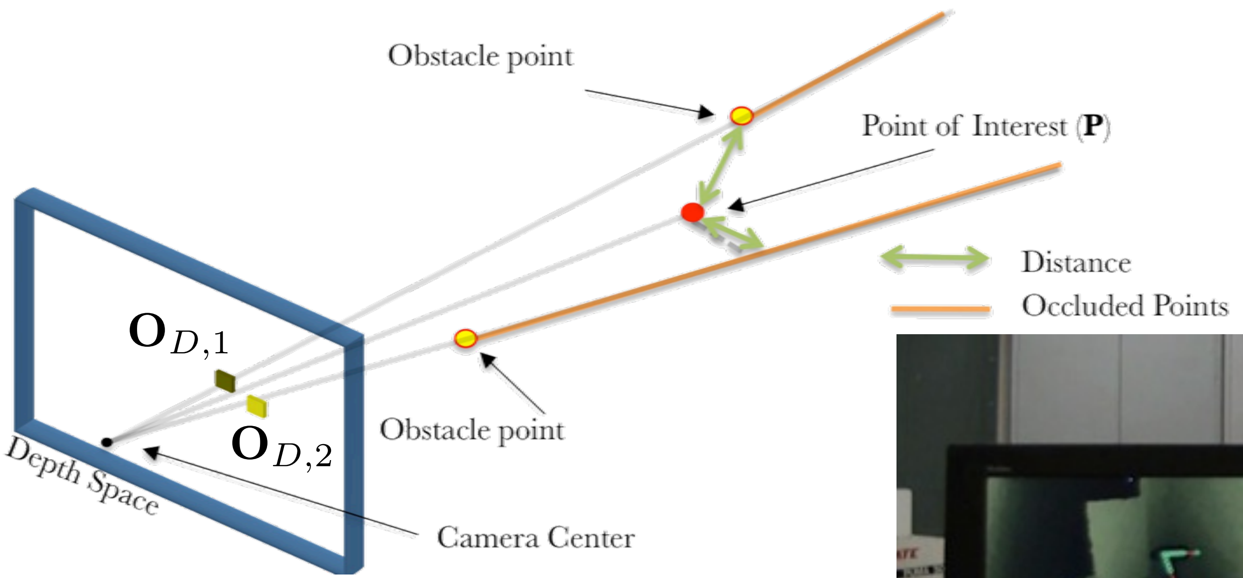
Distance evaluation

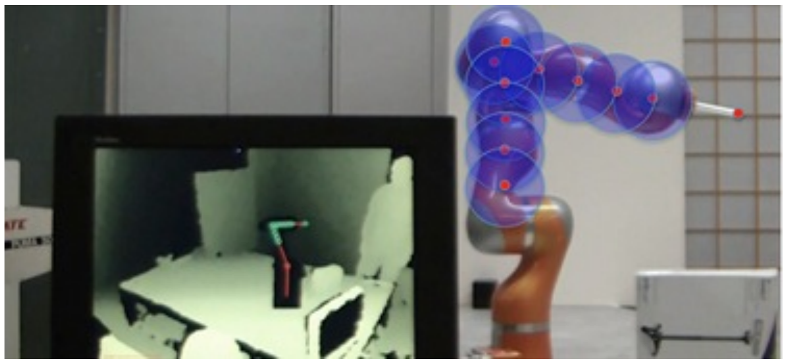
- distance between a point of interest $\boldsymbol{P}_D = (p_x, p_y, d_p)$ and an obstacle point $\mathbf{O}_D = (o_x, o_y, d_o)$

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

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

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



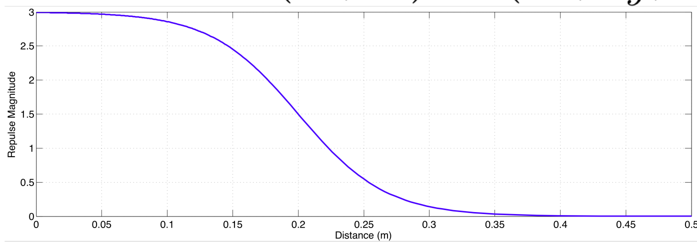


Repulsive vector

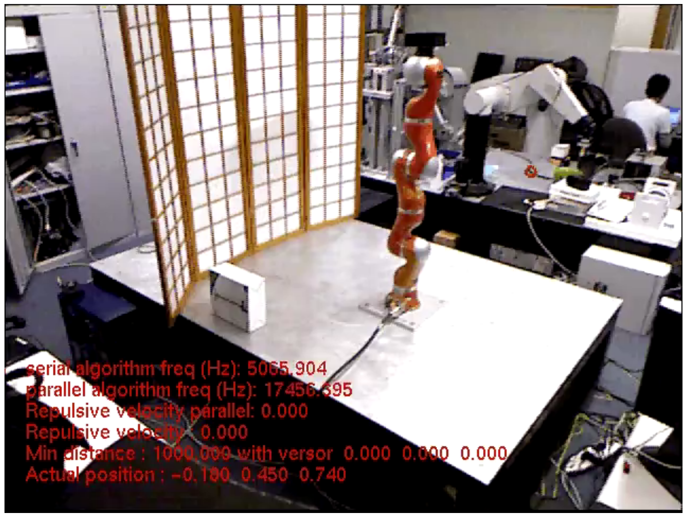
A version of artificial potentials

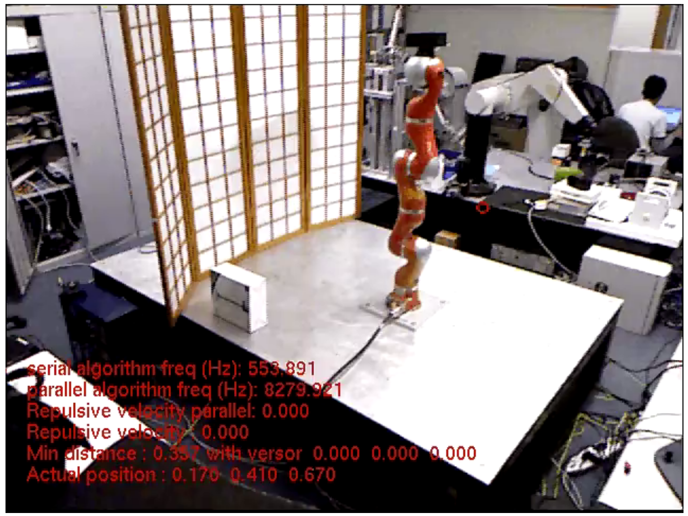
- repulsive vector generated from the distance vector $\boldsymbol{D}(\boldsymbol{P},\mathbf{O}) = (v_x, v_y, v_z)$

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



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





Safe coexistence

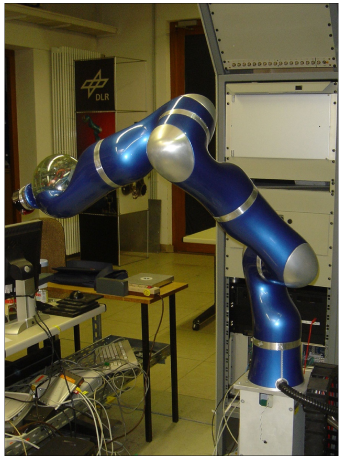
Collision avoidance in depth space

SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction

Human and Robot share the same workspace...

What about using industrial robots?

From DLR LWR-III and KUKA LWR 4 to commercial manipulators



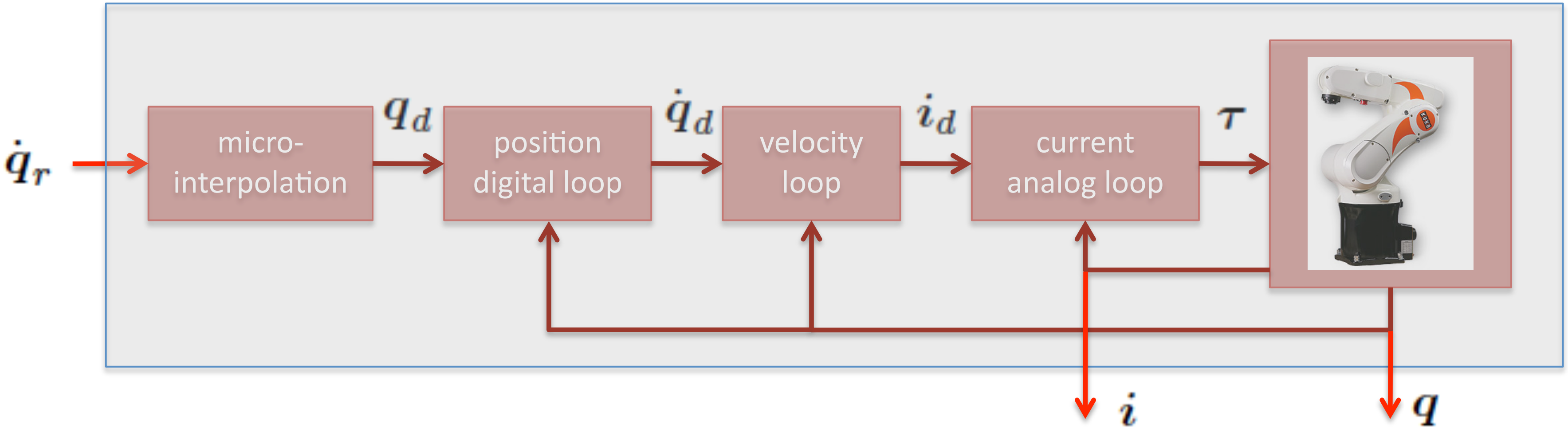
- 7-dof human-arm size, weight = 14 kg = payload
- dynamic model available
- joint torque sensor available
- torque controlled
- Fast Research Interface (FRI) @1 ms, with access to motor current commands

- 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 encoder positions and 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

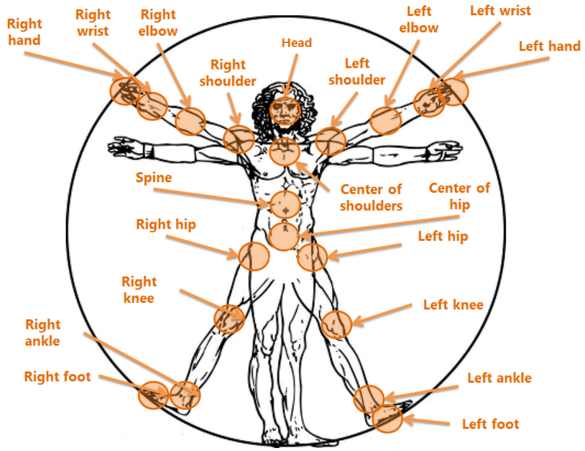


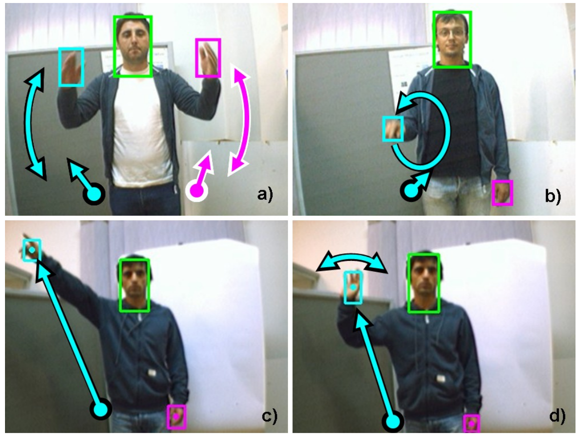
- the external reference velocity can be updated (every 12 ms), based on encoder and motor current readings + external sensor information
  - no torque or current command can be imposed
  - relies on the "good" properties of the low-level (P/PD/PID) KUKA controllers
- a reference velocity could be computed so as to apply a desired torque to the robot ("torque transformer" method by O. Khatib)
  - based on inverting the closed-loop plant
  - needs knowledge of robot dynamics and of low-level control laws & parameters

Contactless collaboration

Using gesture and voice commands

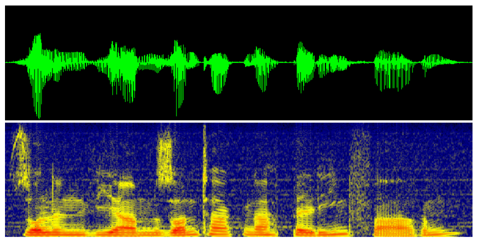
- human body parts and gesture recognition





- speech recognition

Voice command

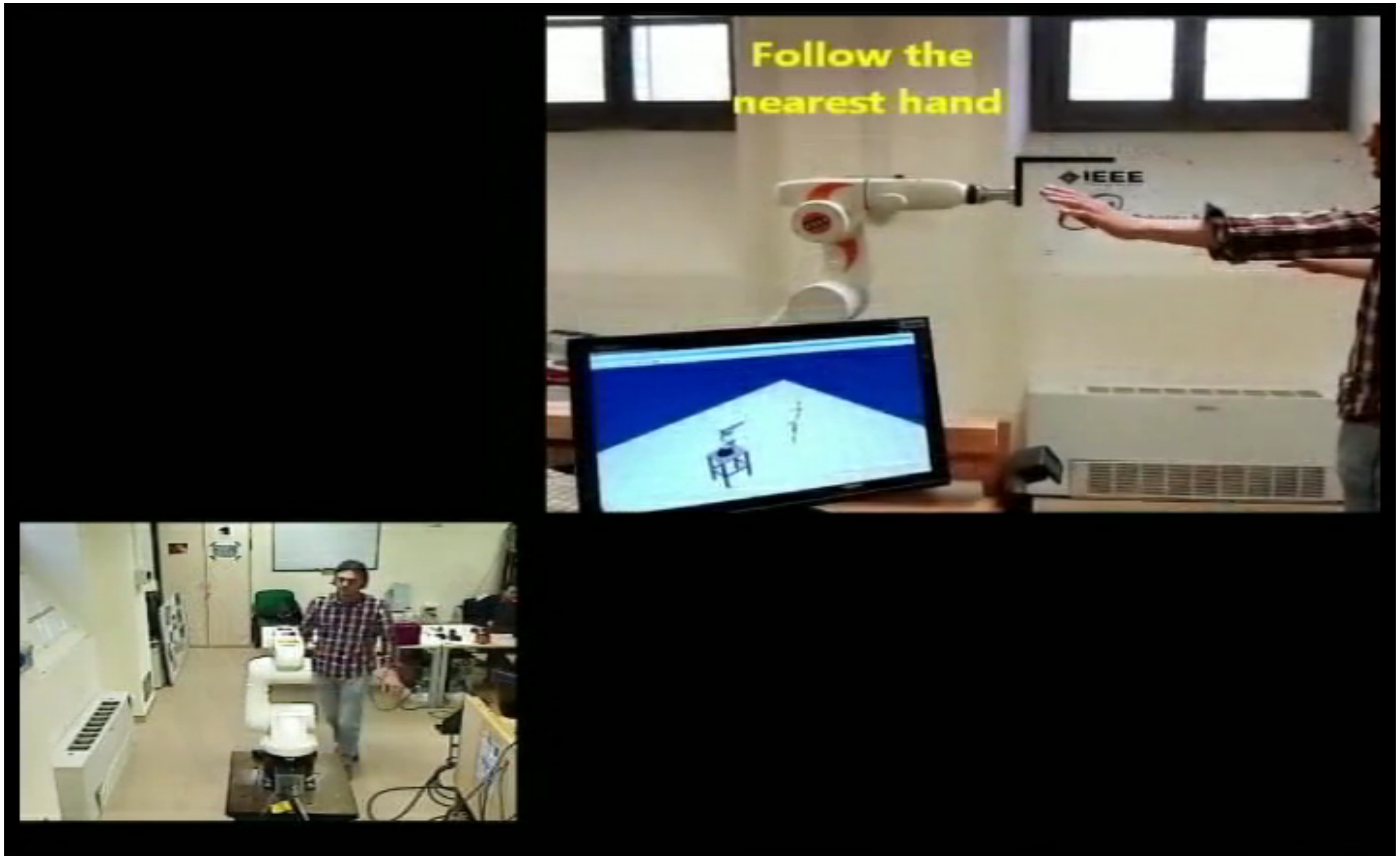


Collaboration starts

Human-robot communication

Using MS Kinect and SDK library

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

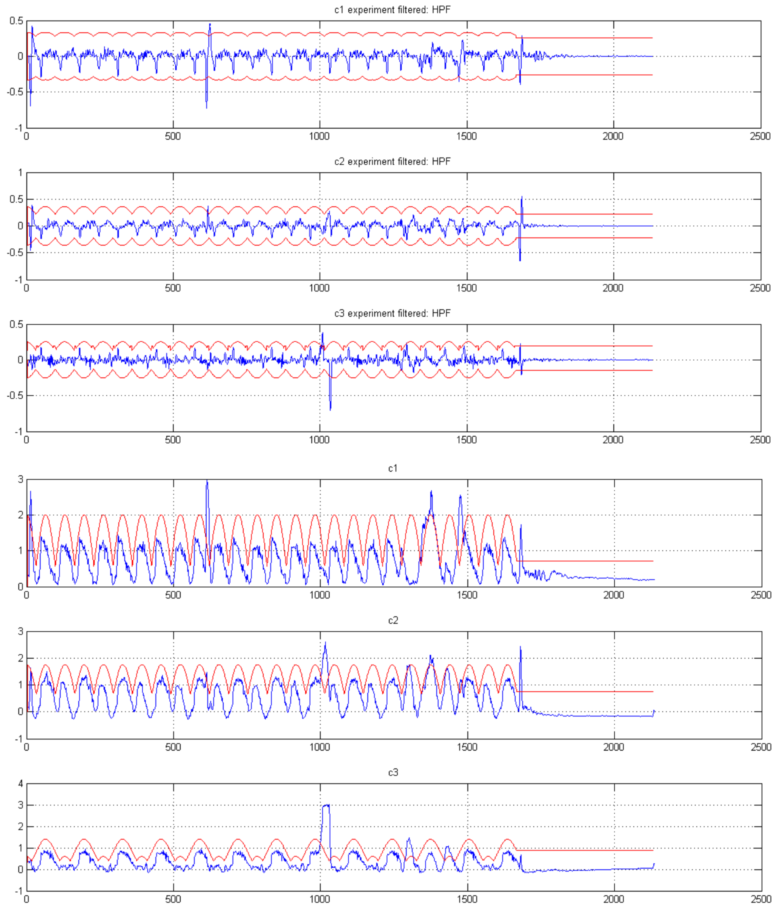


Human stopping the robot

Signal-based collision detection processing motor currents

- detection of collisions and temporary stop
  - no force sensing, no dynamic model, closed architecture (here: work with 3 joints only)
  - low-pass (LPF) and high-pass (HPF) filtering of measured motor currents used in parallel

time-varying thresholds depend only on commanded velocity and acceleration



HPF

LPF

Designing robot reaction strategies

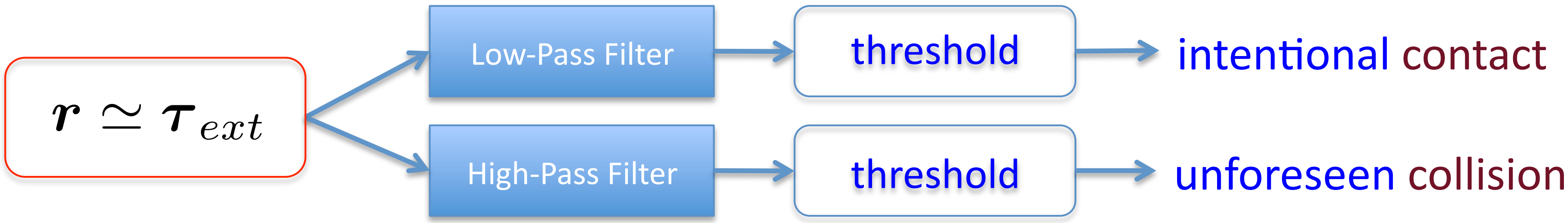
Detect collision & stop / Detect interaction intent, stop, float away upon contacts / Imposing a compliant-like behaviour

- distinguish undesired collisions *(hard)* from human intention to interact *(soft)*, by looking at motor current HPF and LPF alarms (HPF off, LPF on in latter case)

Contact force estimation

Combining internal and external sensing

similarly to what done for the currents, by processing the residual (external forces) in the frequency domain, it is possible to distinguish



for intentional contacts, Kinect data are used to locate contact points

using the Jacobians $\boldsymbol{J}_k(\boldsymbol{q})$ associated to the contact points, external forces can be estimated (without the need of force/torque sensors!) as

$$\begin{pmatrix} \widehat{\boldsymbol{F}}_1 \\ \widehat{\boldsymbol{F}}_2 \end{pmatrix} = \begin{pmatrix} \boldsymbol{J}_1^T(\boldsymbol{q}) & \boldsymbol{J}_2^T(\boldsymbol{q}) \end{pmatrix}^{\#} \boldsymbol{r} \qquad (k = 2)$$

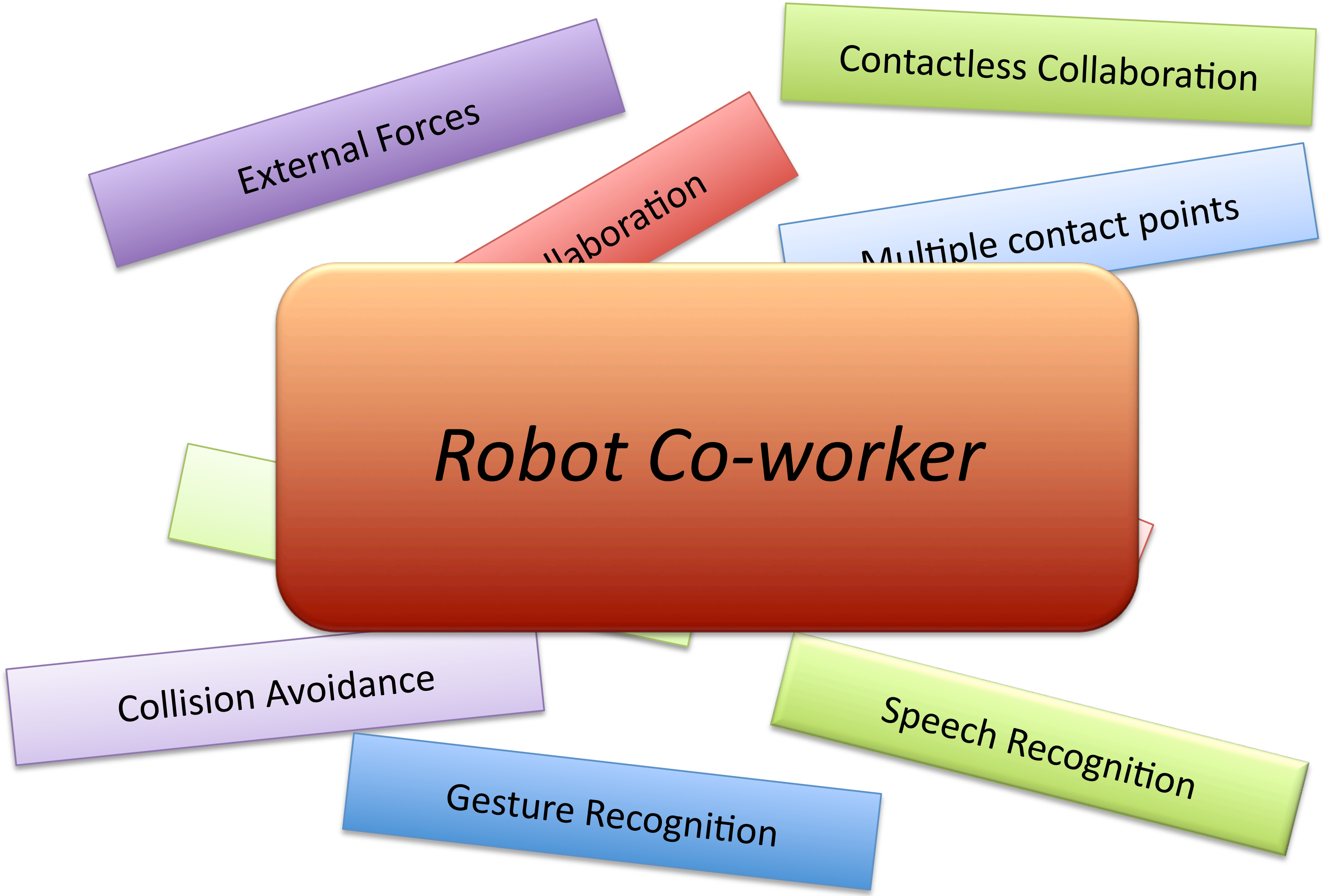
estimates of the external forces can be used for controlling the robot (e.g., by an impedance scheme) at the Cartesian level

Safe physical collaboration

Robot searching for contact with designated human part (one of the hands)

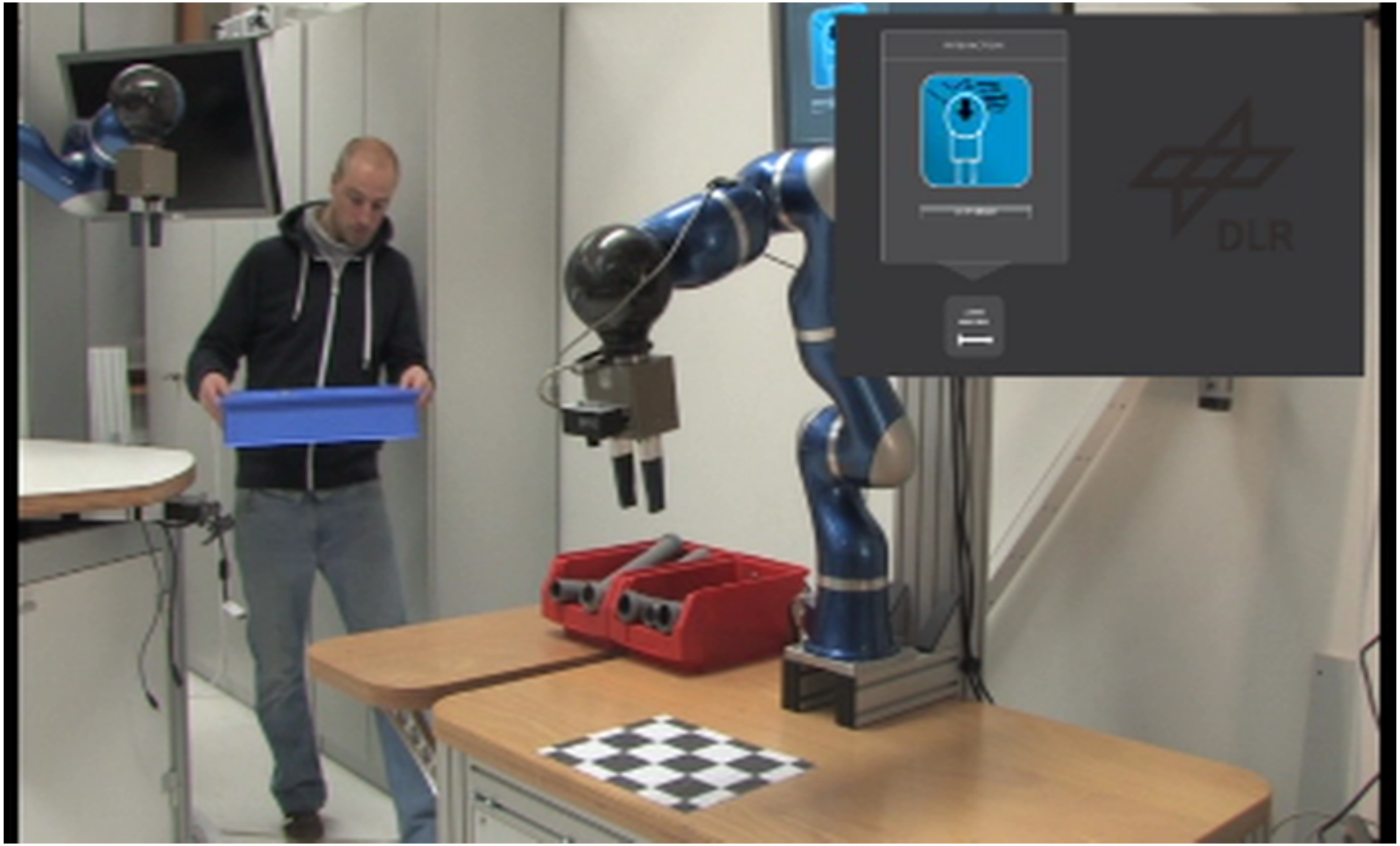
Safe collaboration

Merging all together



Robot co-worker

Physical HRI during task execution, with friendly user interface (@DLR)



A further use of pHRI

Learning by human imitation and incremental kinesthetic refinement (@TUM)

Conclusions

Toward human-robot safe physical collaboration

- a unified framework for safe human-robot collaboration, based on a hierarchy of consistent behaviours that the robot must accomplish
  - residual-based collision detection
  - portfolio of collision reaction algorithms
  - collision avoidance based on depth space data
  - gesture and speech for contactless collaboration
  - contact force estimator

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