Robotics 2

Collision detection and robot reaction

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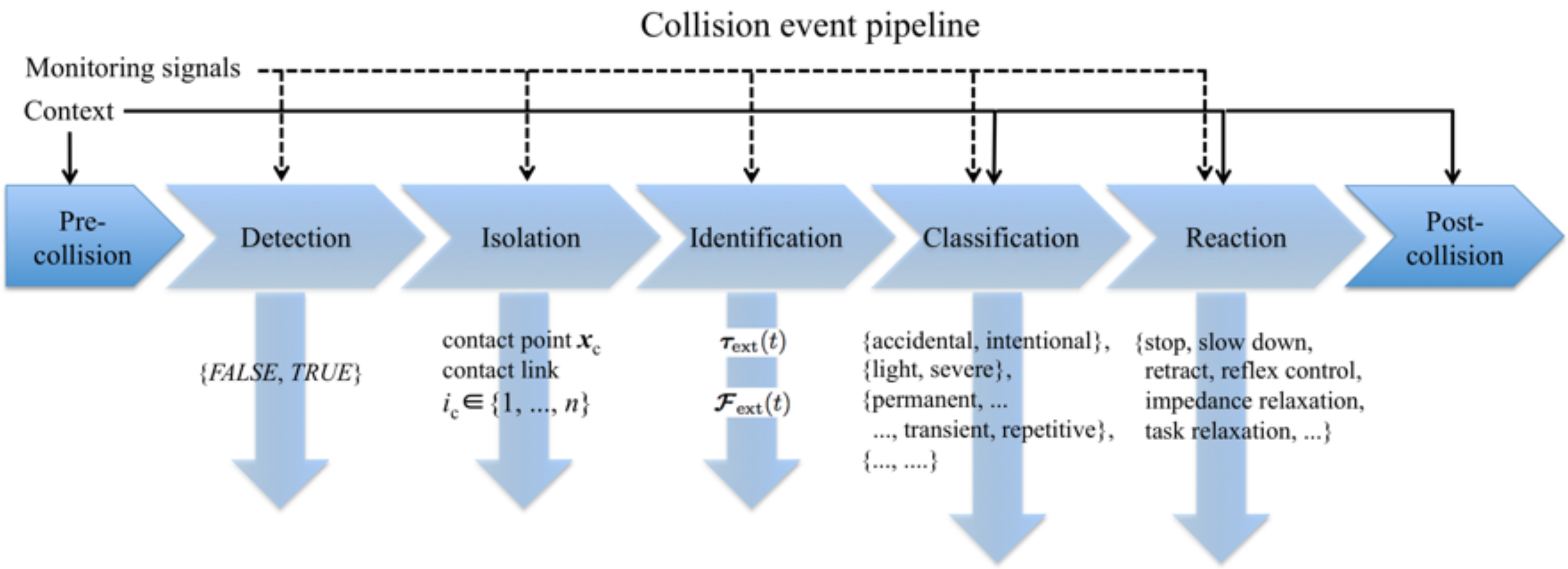
Handling of robot collisions

- safety in physical Human-Robot Interaction (pHRI)
- robot dependability (i.e., beyond reliability)
  - mechanics: lightweight construction and inclusion of compliance
  - next generation with 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, detect and react to collisions
  - possibly, using only robot proprioceptive sensors
- different phases in the collision event pipeline

PHRIENDS FP6 STREP (2006-09) → SAPHARI FP7 IP (2011-15) → SYMPLEXITY H2020 IP (2015-18)

European projects that have funded our research developments

Collision event pipeline



S. Haddadin, A. De Luca, A. Albu-Schäffer: "Robot Collisions: A Survey on Detection, Isolation, and Identification," *IEEE Trans. on Robotics*, vol. 33, no. 6, pp. 1292-1312, 2017

Collision detection in industrial robots

- advanced option available for some robots (ABB, KUKA, UR ...)
- allow only detection, not isolation
  - based on large variations of control torques (or motor currents)

$$\|\tau(t_k) - \tau(t_{k-1})\| \geq \varepsilon \quad \Leftrightarrow \quad |\tau_i(t_k) - \tau_i(t_{k-1})| \geq \varepsilon_i, \text{ for at least one joint } i$$

  - based on comparison with nominal torques on a desired trajectory

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

  - based on robot state and numerical estimate of acceleration

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

  - based on the parallel simulation of robot dynamics

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

- 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

video

- the only feasible robot reaction is to stop!

Collisions as system faults

- robot model with (possible) collisions

control torque

$$M(q)\ddot{q} + S(q,\dot{q})\dot{q} + g(q) = \tau + \tau_K = \tau_{\text{tot}}$$

inertia matrix

Coriolis/centrifugal (with "good" factorization): $\dot{M} - 2S$ is skew-symmetric

joint torque caused by link collision

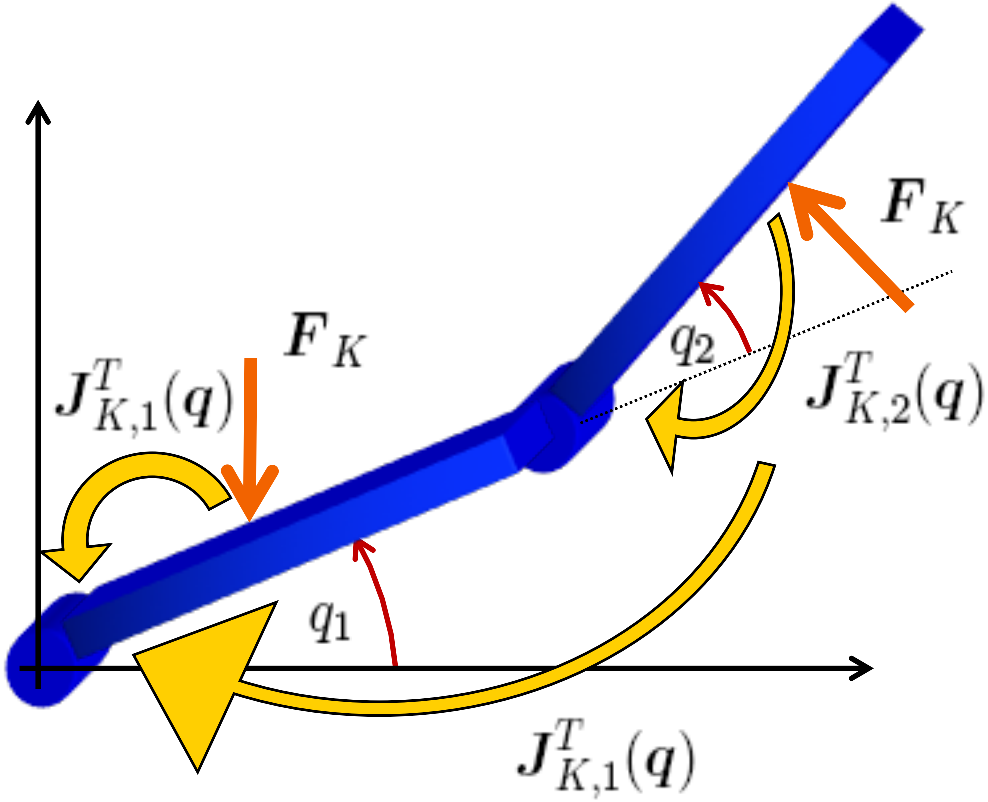
$$\boxed{\tau_K = J_K^T(q) F_K}$$

with transpose of the Jacobian associated to the contact point/area

- collisions may occur at any (unknown) location along the whole robotic structure
- simplifying assumptions (some may be relaxed)
  - manipulator is an open kinematic chain
  - single contact/collision
  - negligible friction (or has to be identified and used in the model)

Analysis of a collision

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



in static conditions a contact force/torque on ith link is balanced ONLY by torques at preceding joints $j \leq i$

in dynamic conditions a contact force/torque on ith link produces accelerations at ALL joints

Relevant dynamic properties

- 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 momentum and its decoupled dynamics

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

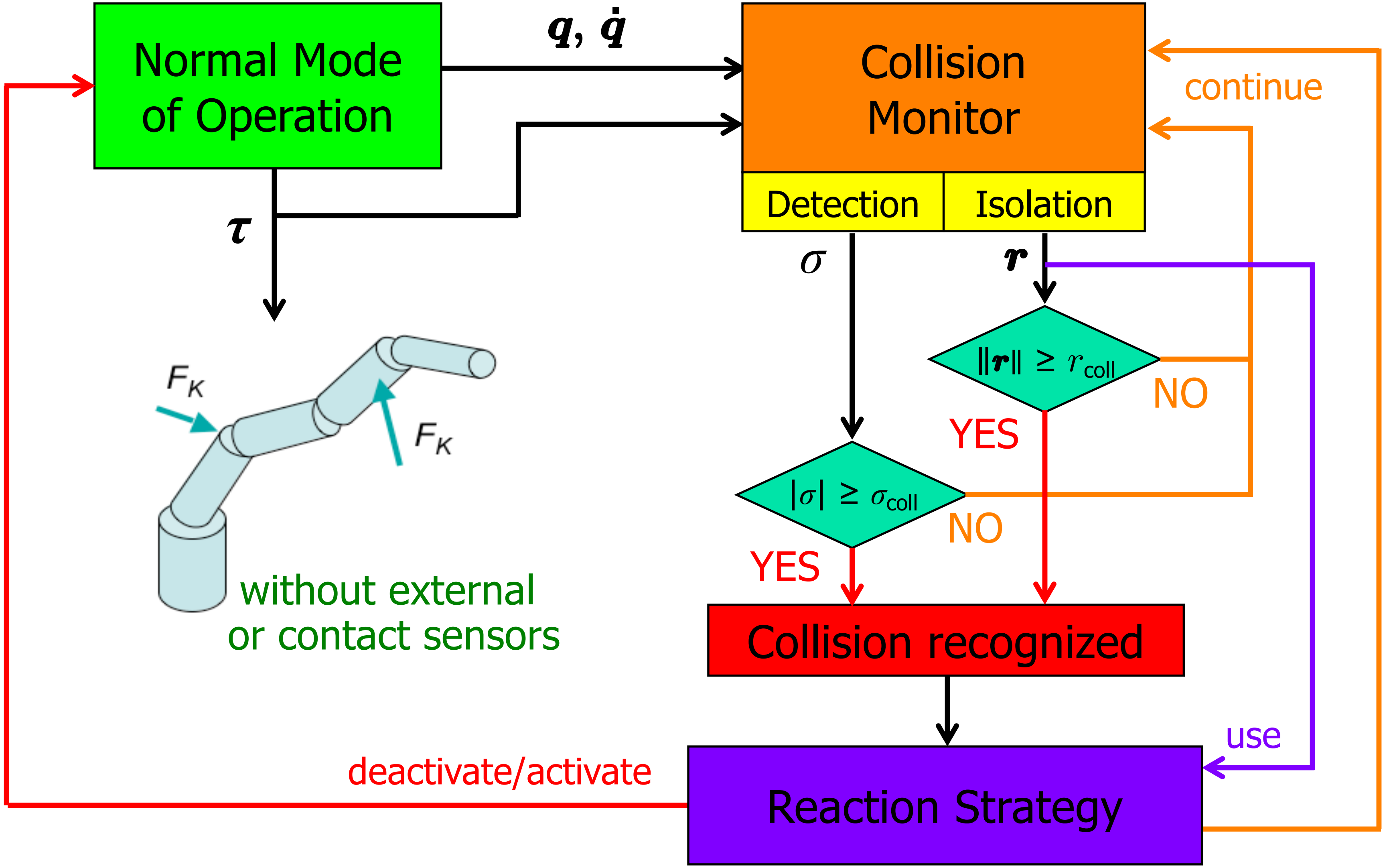
$$\dot{\boldsymbol{p}} = \boldsymbol{\tau}_{\mathrm{tot}} + \boldsymbol{S}^T(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q})$$

NOTE: this is a vector version of the same formula already encountered in actuator FDI

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

Ex: prove this expression!

Monitoring collisions



Energy-based detection of collisions

- scalar residual (computable) also via N-E algorithm!

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

$$\sigma(0) = 0 \qquad\qquad k_D > 0$$

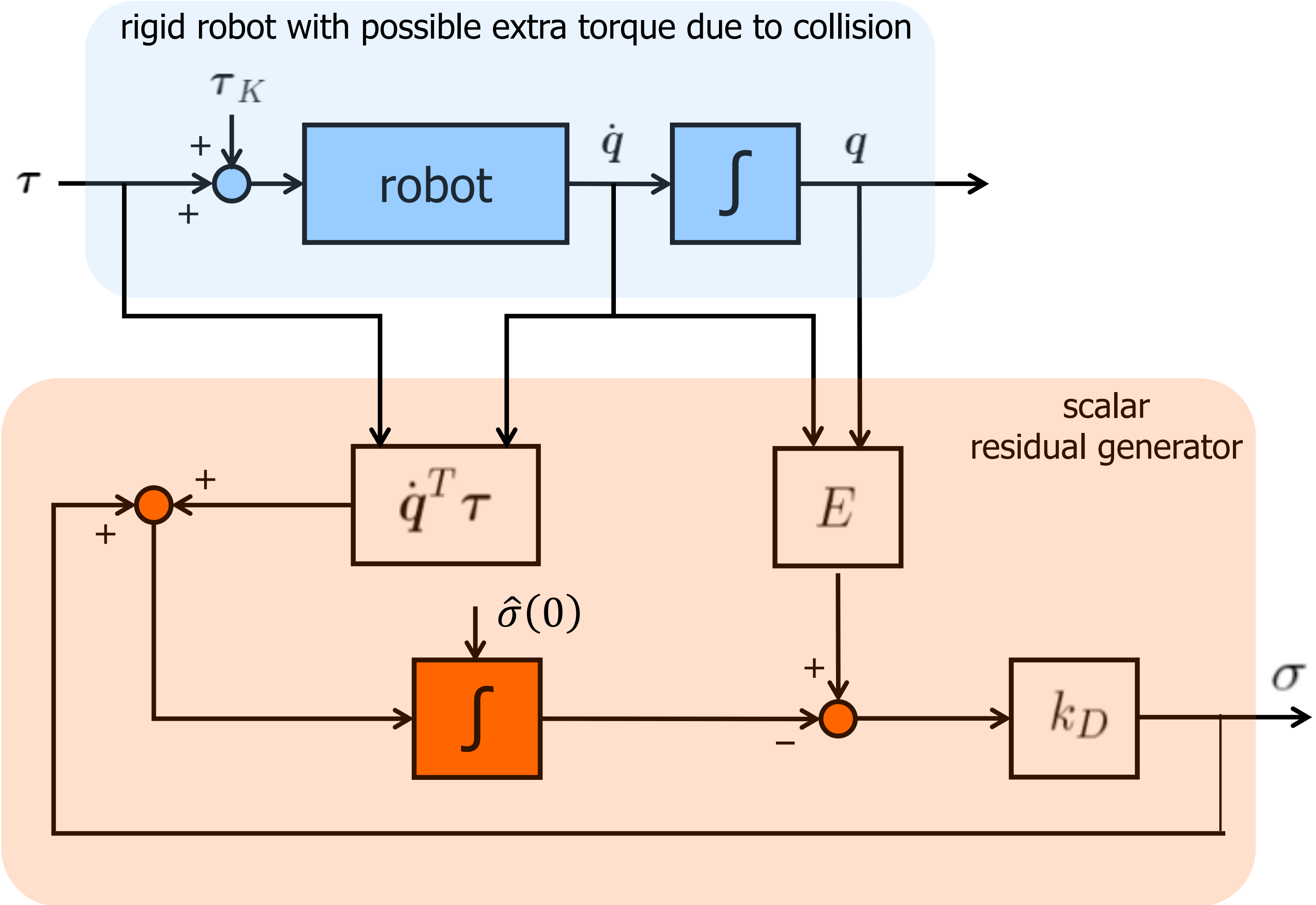
- … and its dynamics (needed only for analysis)

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

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

Block diagram of residual generator

energy-based scalar signal



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

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

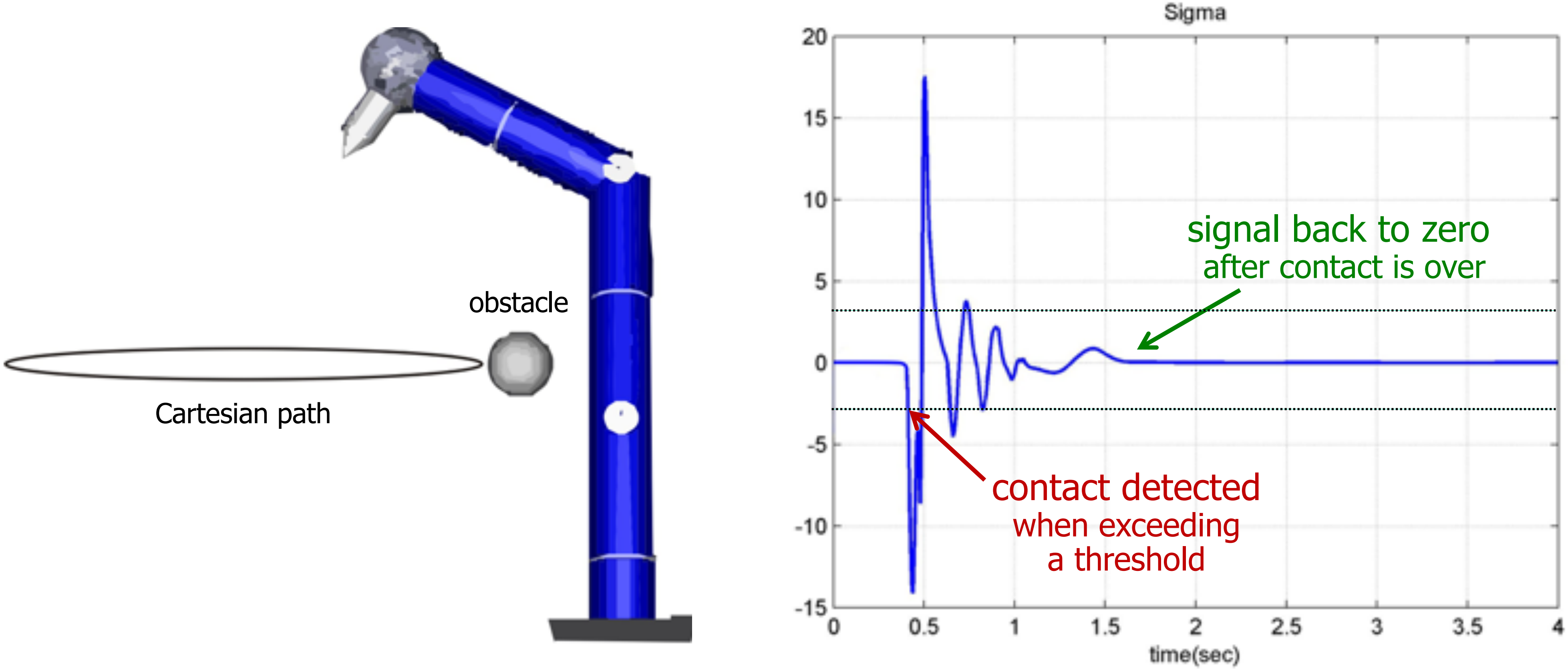
Analysis of the energy-based method

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

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

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

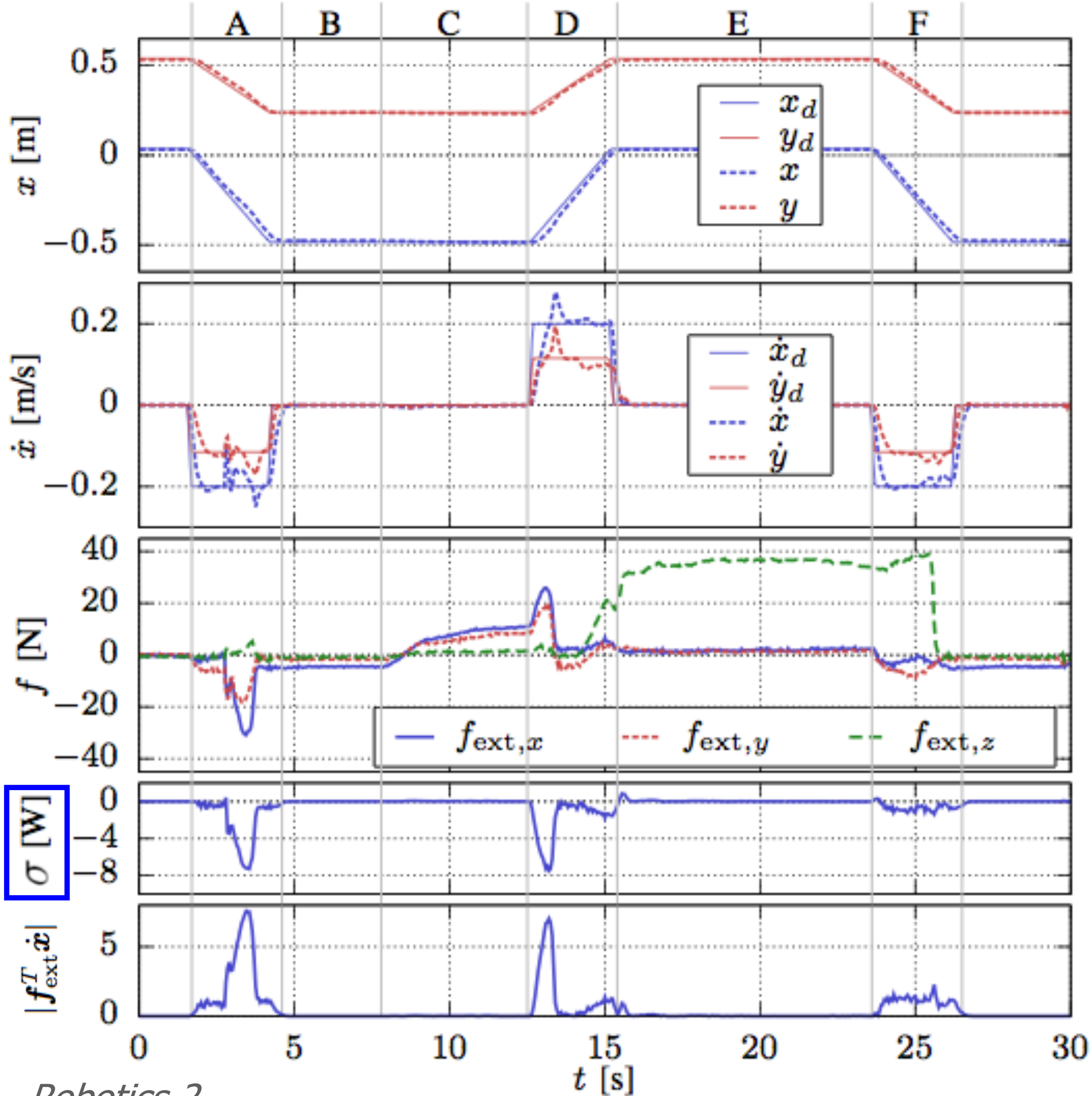
Collision detection
simulation with a 7R robot



detection of a collision with a fixed obstacle in the work space during the execution of a Cartesian trajectory (redundant robot)

Collision detection

experiment with a 6R robot



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

6 phases

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

B: no force applied, with robot at rest

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

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

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

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

Momentum-based isolation of collisions

- residual vector (computable)

in case, needs modified N-E algorithm!

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

$$\boldsymbol{r}(0) = \boldsymbol{0} \qquad \boldsymbol{K}_I > \boldsymbol{0} \text{ (diagonal)}$$

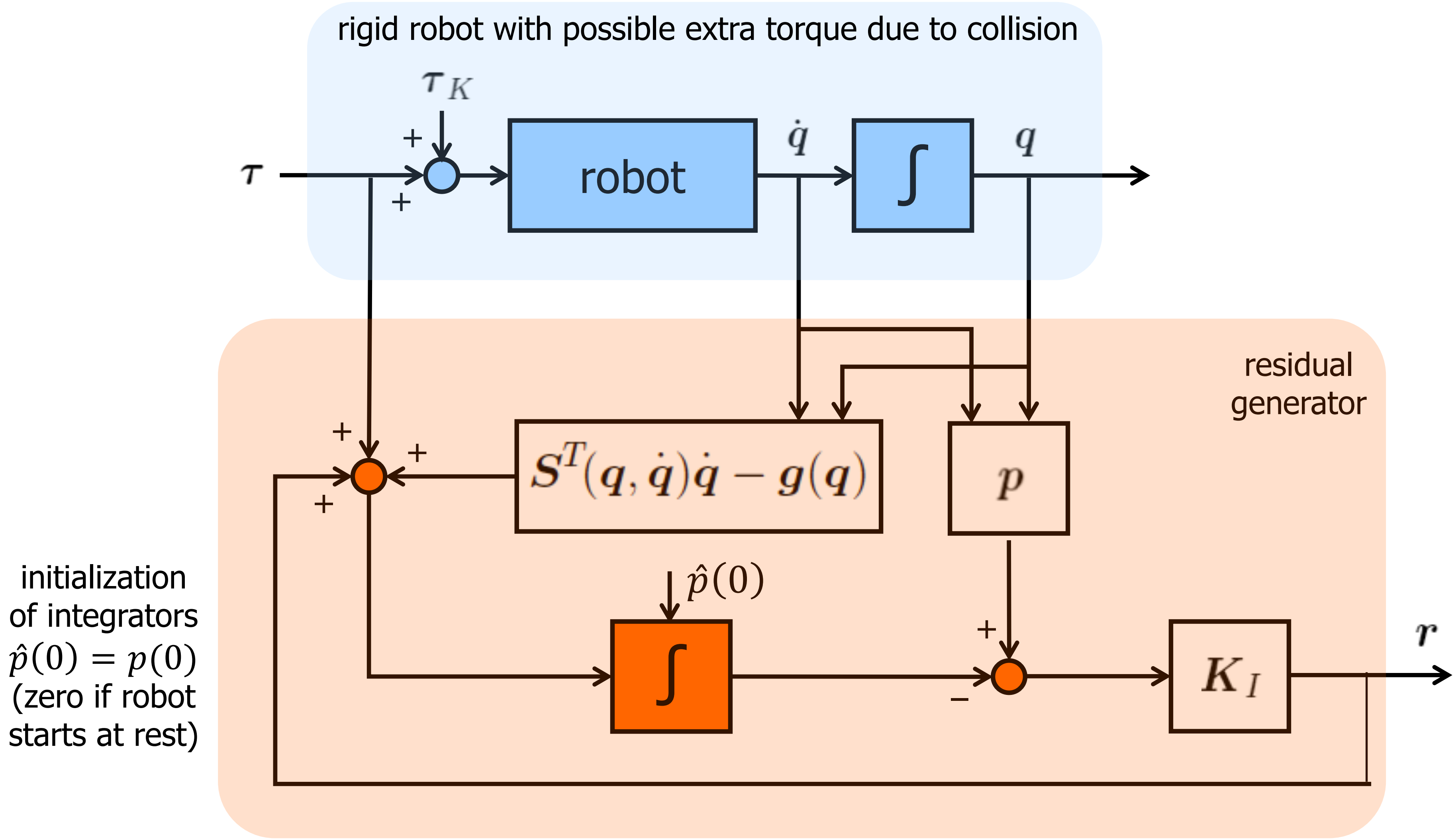
- ... and its decoupled dynamics

$$\dot{\boldsymbol{r}} = -\boldsymbol{K}_I \boldsymbol{r} + \boldsymbol{K}_I \boldsymbol{\tau}_K \qquad \frac{r_j(s)}{\tau_{K,j}(s)} = \frac{K_{I,j}}{s + K_{I,j}} \quad j = 1, \ldots, N$$

N first-order, linear filters with unitary gains, excited by a collision!
(all residuals go back to zero if there is no longer contact = post-impact phase)

Block diagram of residual generator

momentum-based vector signal



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

Analysis of the momentum method

- ideal situation (no noise/uncertainties)

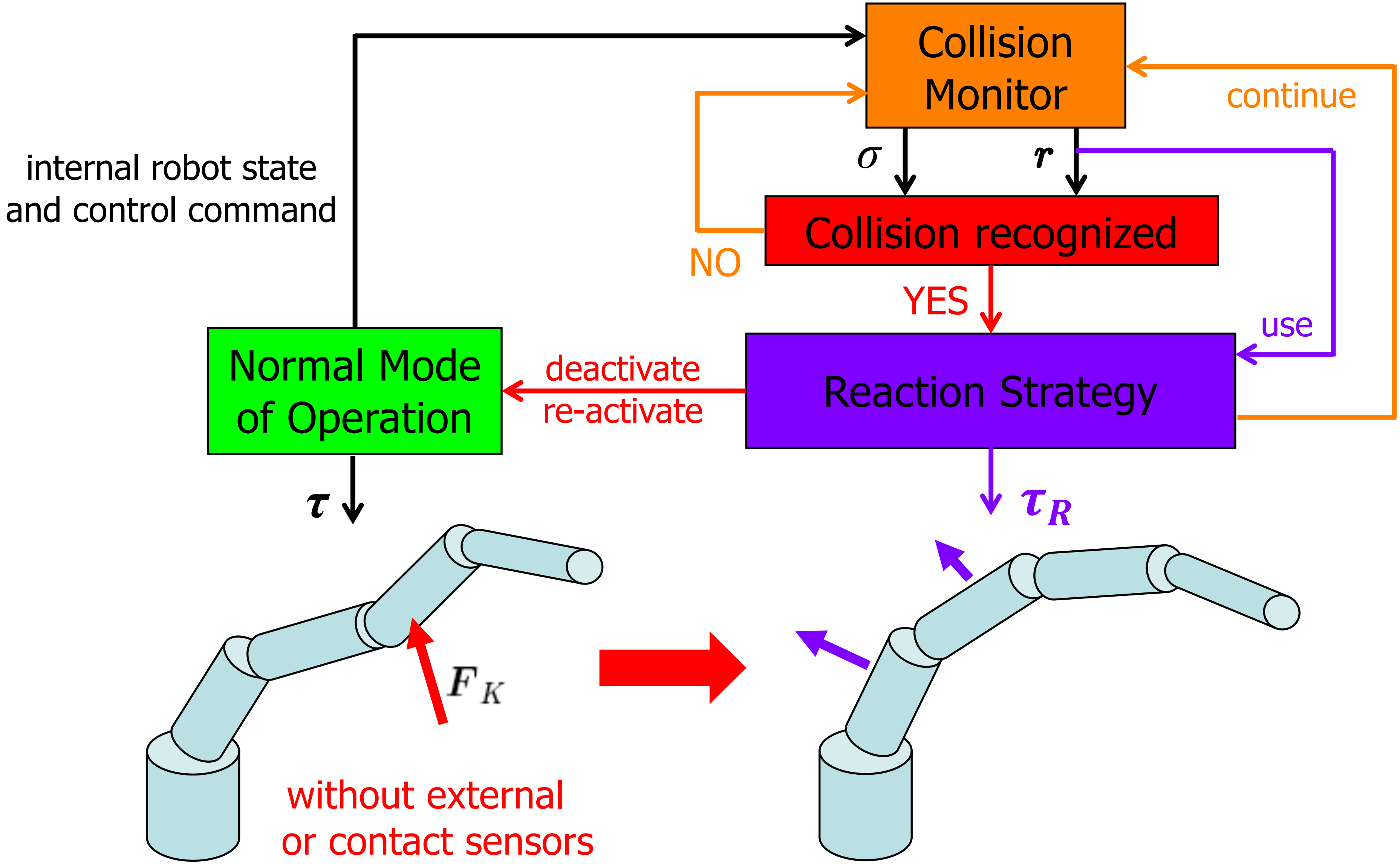
$$\boldsymbol{K}_I \to \infty \quad \Rightarrow \quad \boxed{\boldsymbol{r} \approx \boldsymbol{\tau}_K}$$

- isolation property: collision has generically occurred in an area located up to the ith link if

$$\boldsymbol{r} = \begin{bmatrix} * & \dots & * & * & \boxed{0 \quad \dots \quad 0} \end{bmatrix}^T$$
$$\qquad\qquad\qquad\qquad\qquad \uparrow \qquad\quad \uparrow$$
$$\qquad\qquad\qquad\qquad\qquad i+1 \quad \dots \quad N$$

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

Safe reaction to collisions



Robot reaction strategy

- "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

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

"joint torque command in same direction of collision torque"

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

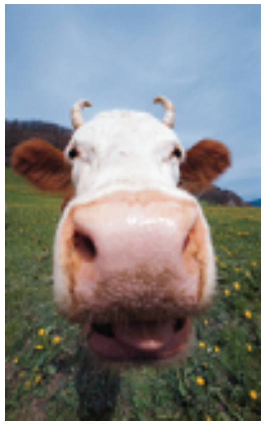
Analysis of the reflex strategy

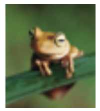
- in ideal conditions, this control strategy is equivalent to a reduction of the effective robot inertia as seen by the collision force/torque

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

"a lighter robot that can be easily pushed way"

from a cow …





... to a frog!

DLR LWR-III robot dynamics

- lightweight (14 kg) 7R anthropomorfic robot with harmonic drives (elastic joints) and joint torque sensors

motor torques commands

joint torques due to link collision

$$
\begin{aligned}
M(q)\ddot{q} + S(q,\dot{q})\dot{q} + g(q) &= \tau_J + \tau_K \\
B_m\ddot{\theta} + \tau_J &= \tau \\
\tau_J &= K(\theta - q)
\end{aligned}
$$

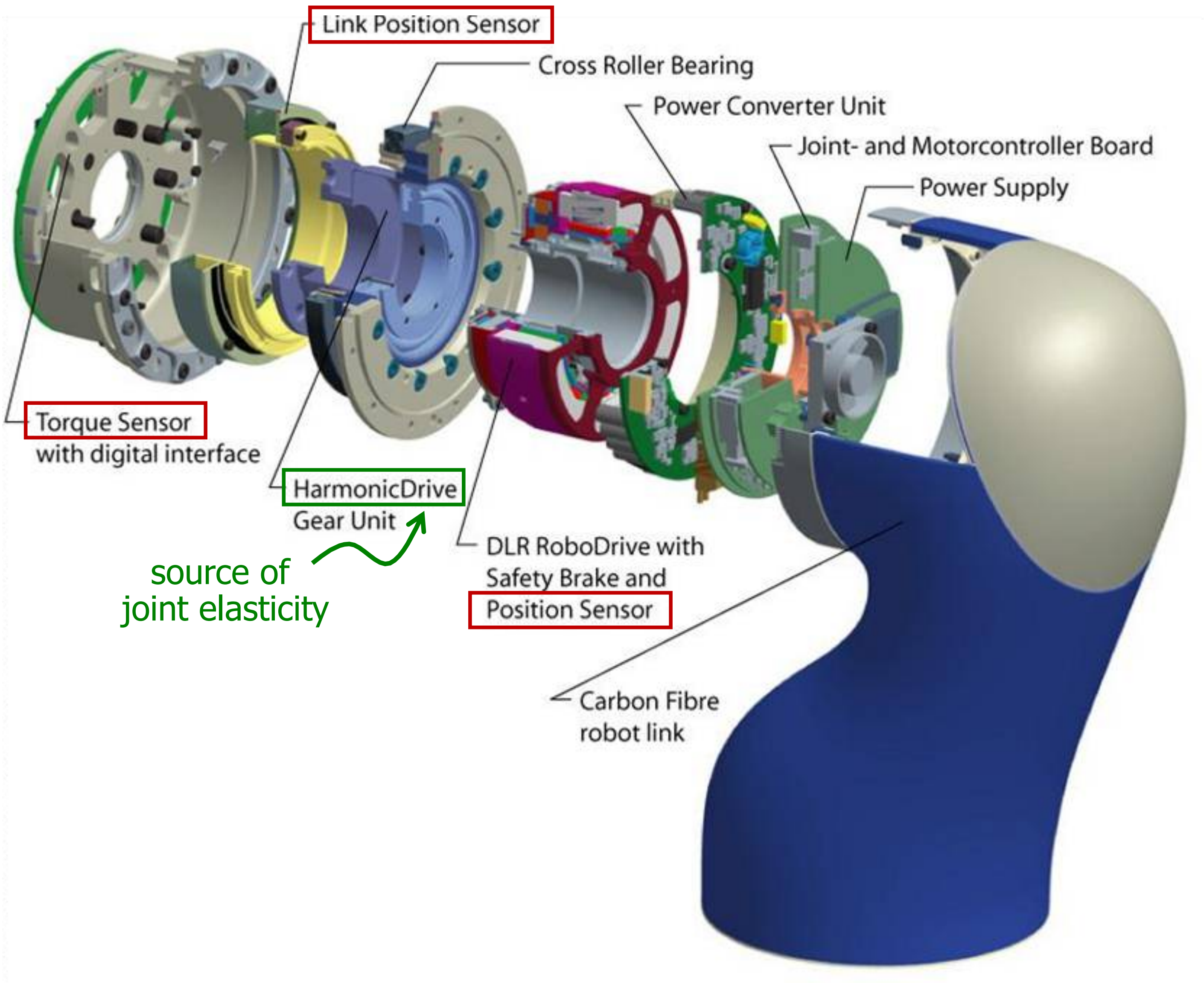
friction at link side is negligible!

elastic torques at the joints

- proprioceptive sensing: motor positions and joint elastic torques

$$\theta \quad \tau_J \quad \Longrightarrow \quad q = \theta - K^{-1}\tau_J$$

Exploded joint of LWR-III robot



Collision isolation for LWR-III robot
elastic joint case

- few alternatives for extending the rigid case results
- for collision isolation, the simplest one takes advantage of the presence of joint torque sensors

$$\boxed{\boldsymbol{\tau} \;\rightarrow\; \boldsymbol{\tau}_J}$$

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

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

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

- other alternatives use
  - link+motor position measures ⇒ needs knowledge also of joint stiffness $\boldsymbol{K}$
  - link+motor momentum + commanded torque ⇒ affected by motor friction
- motion control is more complex in the presence of joint elasticity
- different active strategies of reaction to collisions are possible

Control of DLR LWR-III robot
elastic joint case

- 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 ffw command

- "zero-gravity" condition is realized only in a (quasi-static) approximate 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

Reaction strategies
specific for elastic joint robots

- 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)

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

- 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)

Experiments with LWR-III robot
“dummy” head

dummy head equipped with an accelerometer

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

Dummy head impact

video

video

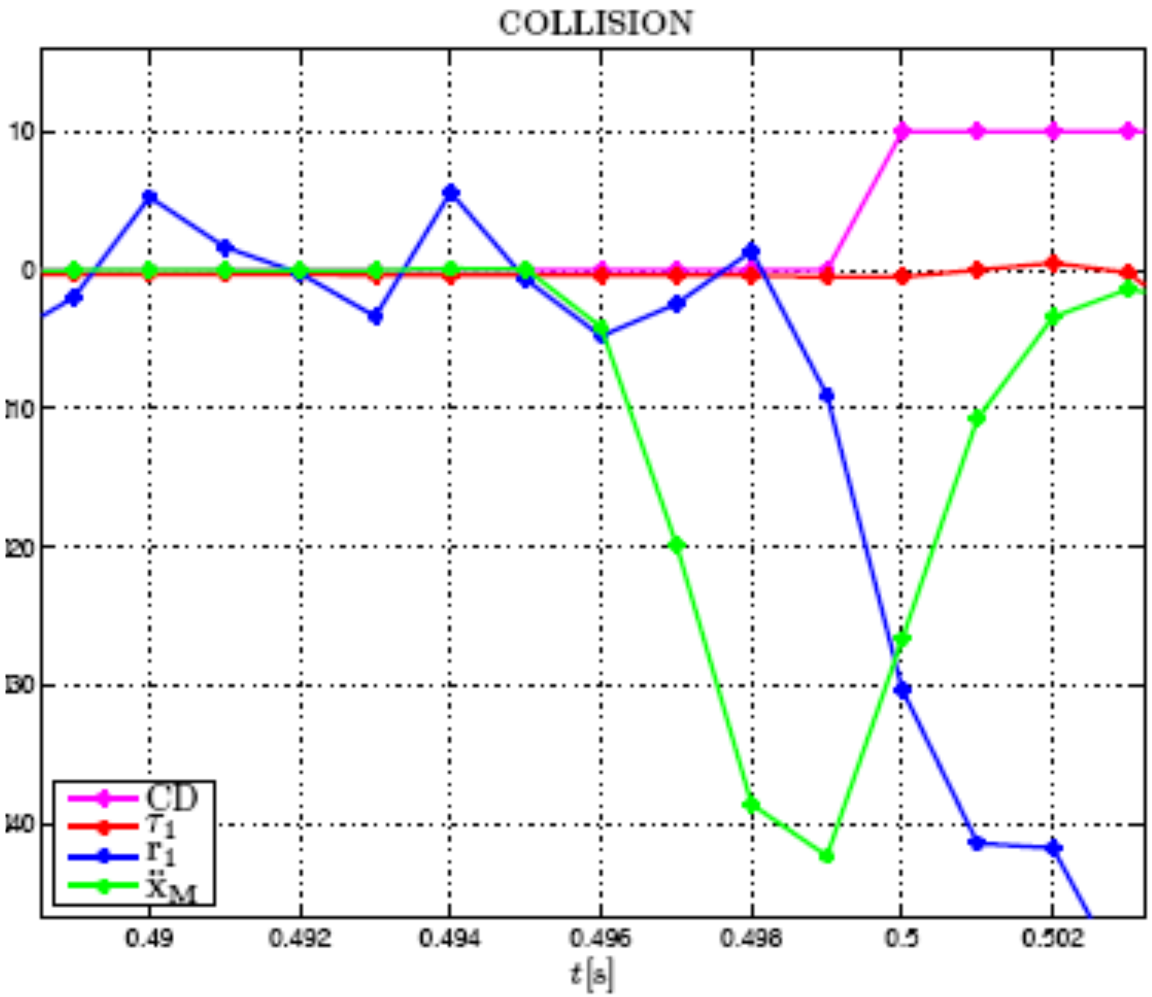
strategy 0: no reaction

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 switching to float mode

Delay in collision detection



2-4 msec!

impact with the dummy head

measured (elastic) joint torque

residual r_1

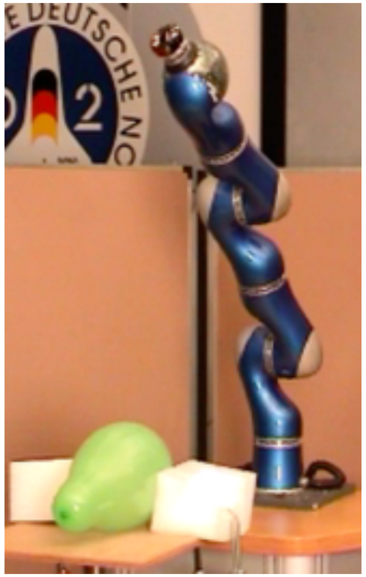
0/1 index for detection

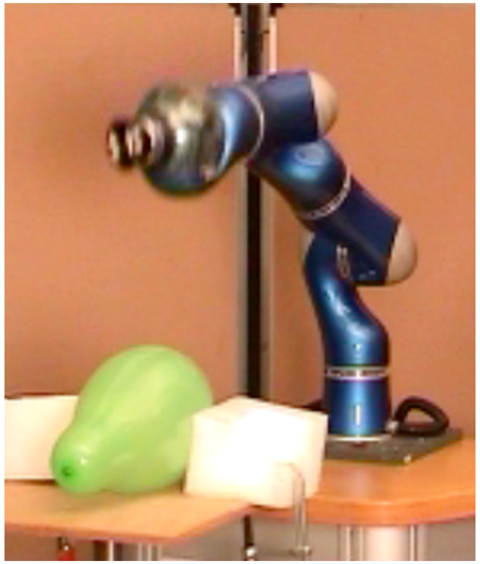
dummy head acceleration

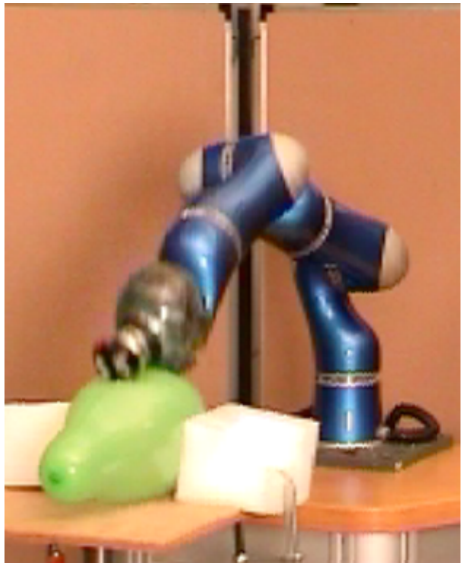
gain K_I = diag{25}

threshold = 5-10% of max rated torque

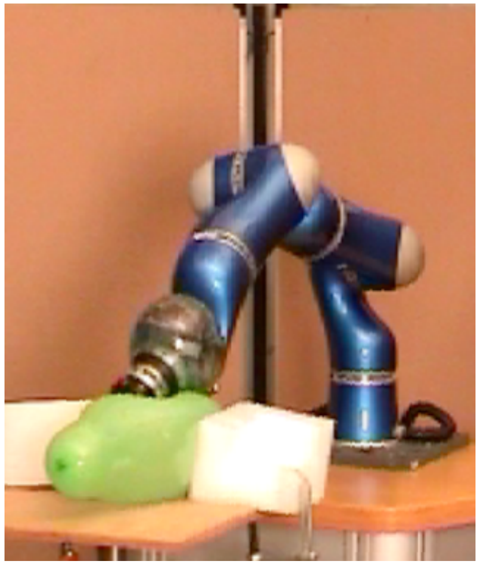
Experiments with LWR-III robot
balloon impact

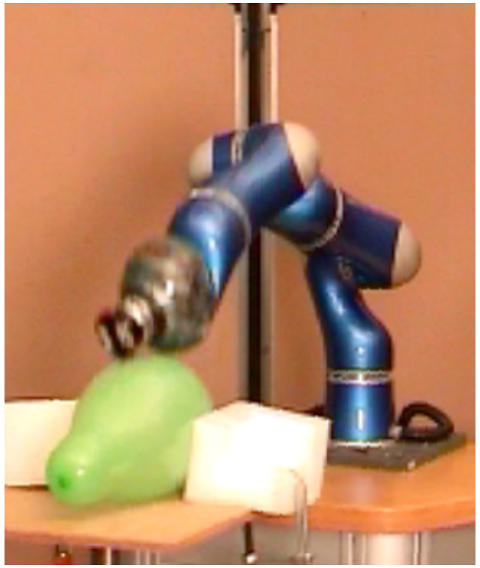


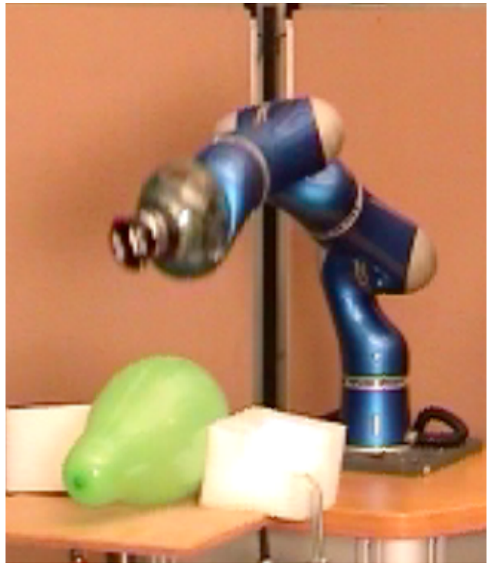




possibility of repeatable comparison of different reaction strategies at high speed conditions







Balloon impact

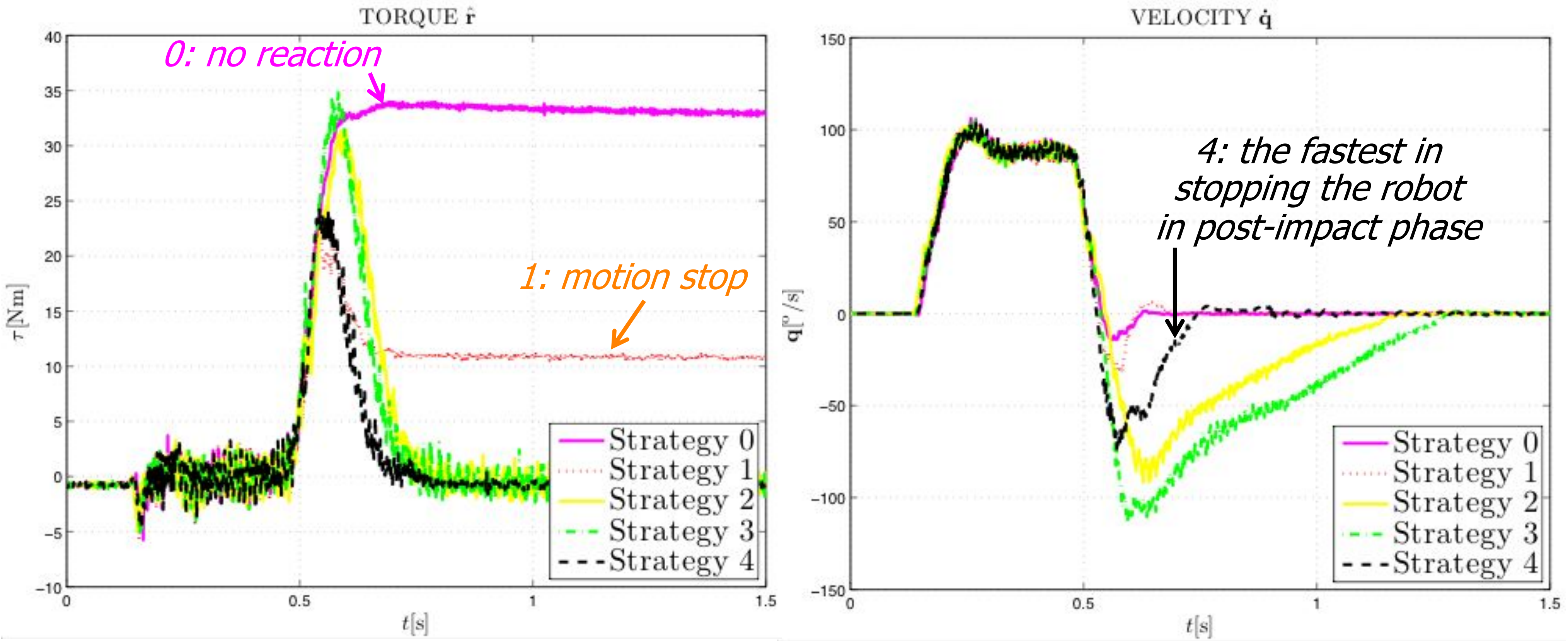
video

coordinated joint motion @90^{o}/sec

strategy 4: admittance mode reaction

Experimental comparison of strategies
balloon impact

- residual and velocity at joint 4 with various reaction strategies



impact at 90°/sec with coordinated joint motion

Human-Robot Interaction – 1

- first impact @60°/sec

video

strategy 4: admittance mode

video

strategy 3: reflex torque

Human-Robot Interaction – 2

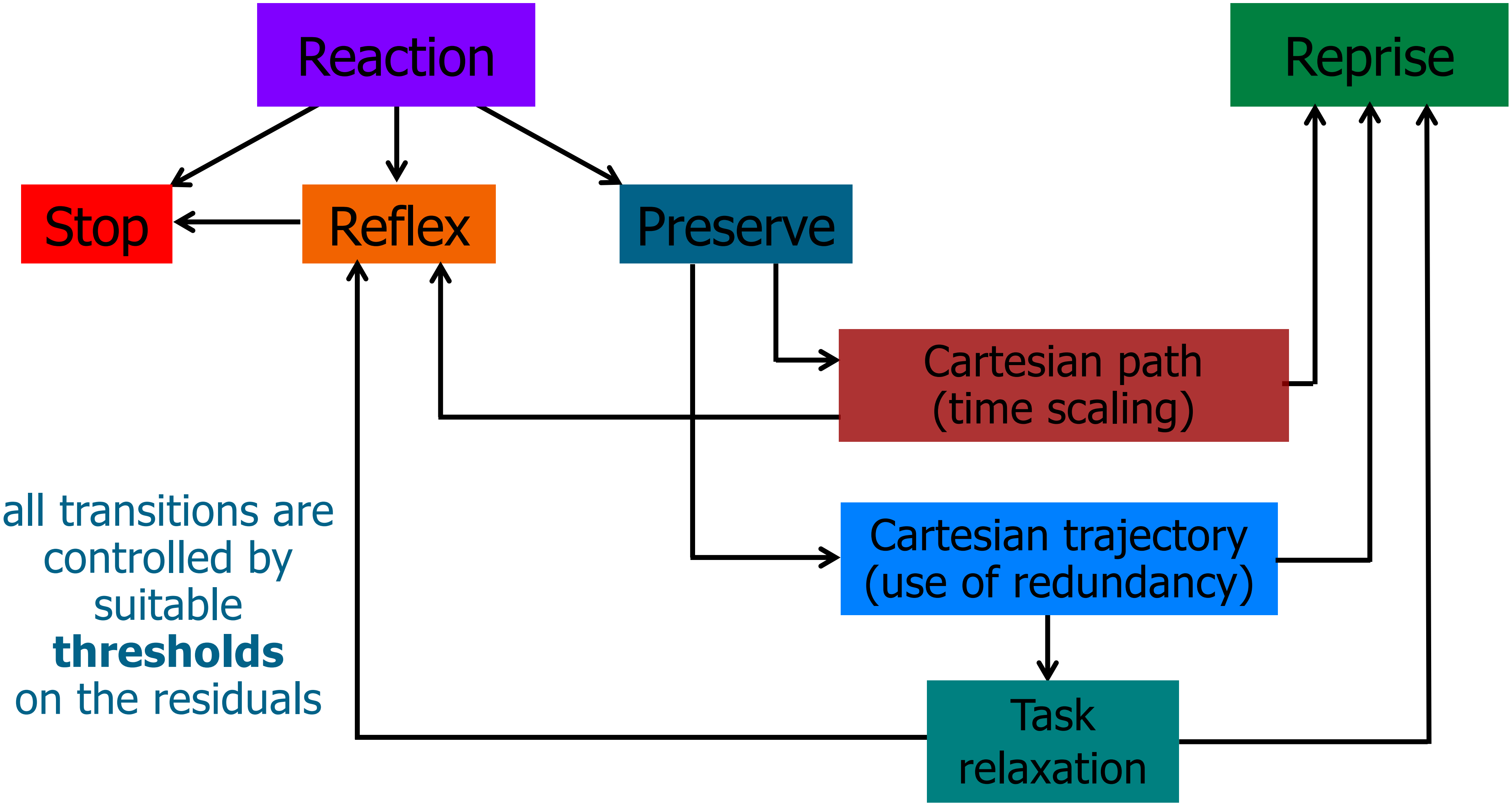
- first impact @90^o/sec

video

strategy 3: reflex torque

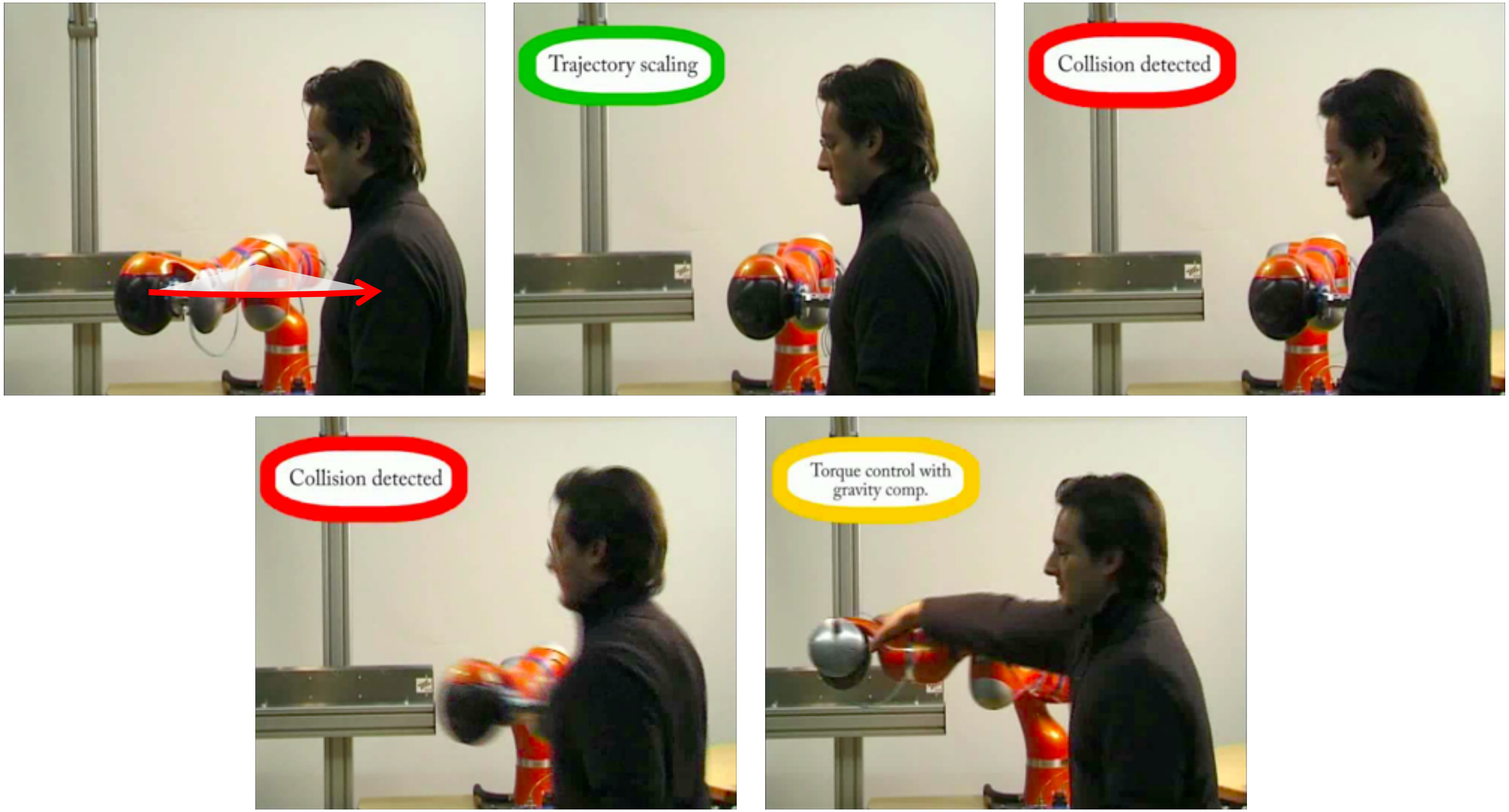
"Portfolio" of reaction strategies

residual amplitude ∝ severity level of collision



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

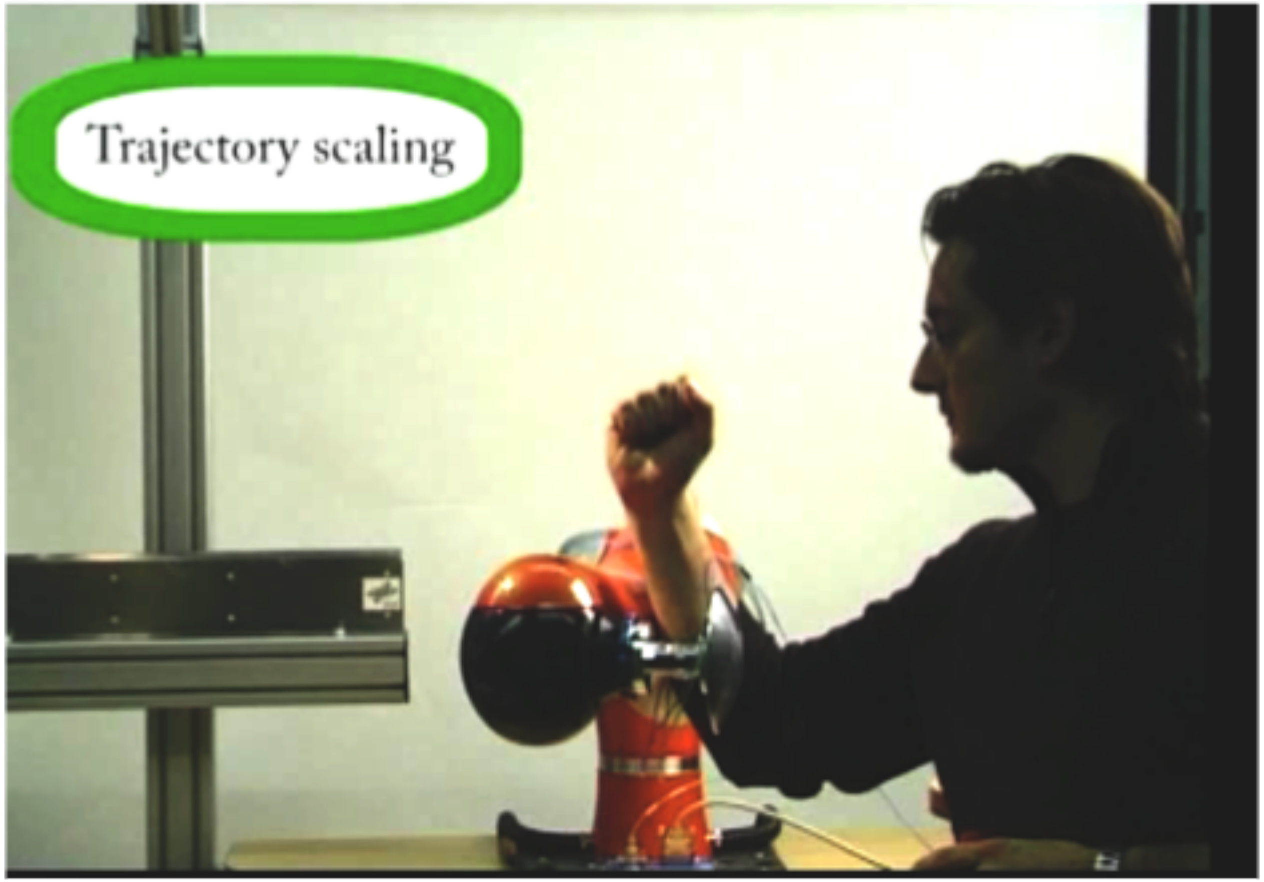
Experiments with LWR-III robot
time scaling



- robot is position-controlled (on a given geometric path)
- timing law slows down, stops, possibly reverses (and then reprises)

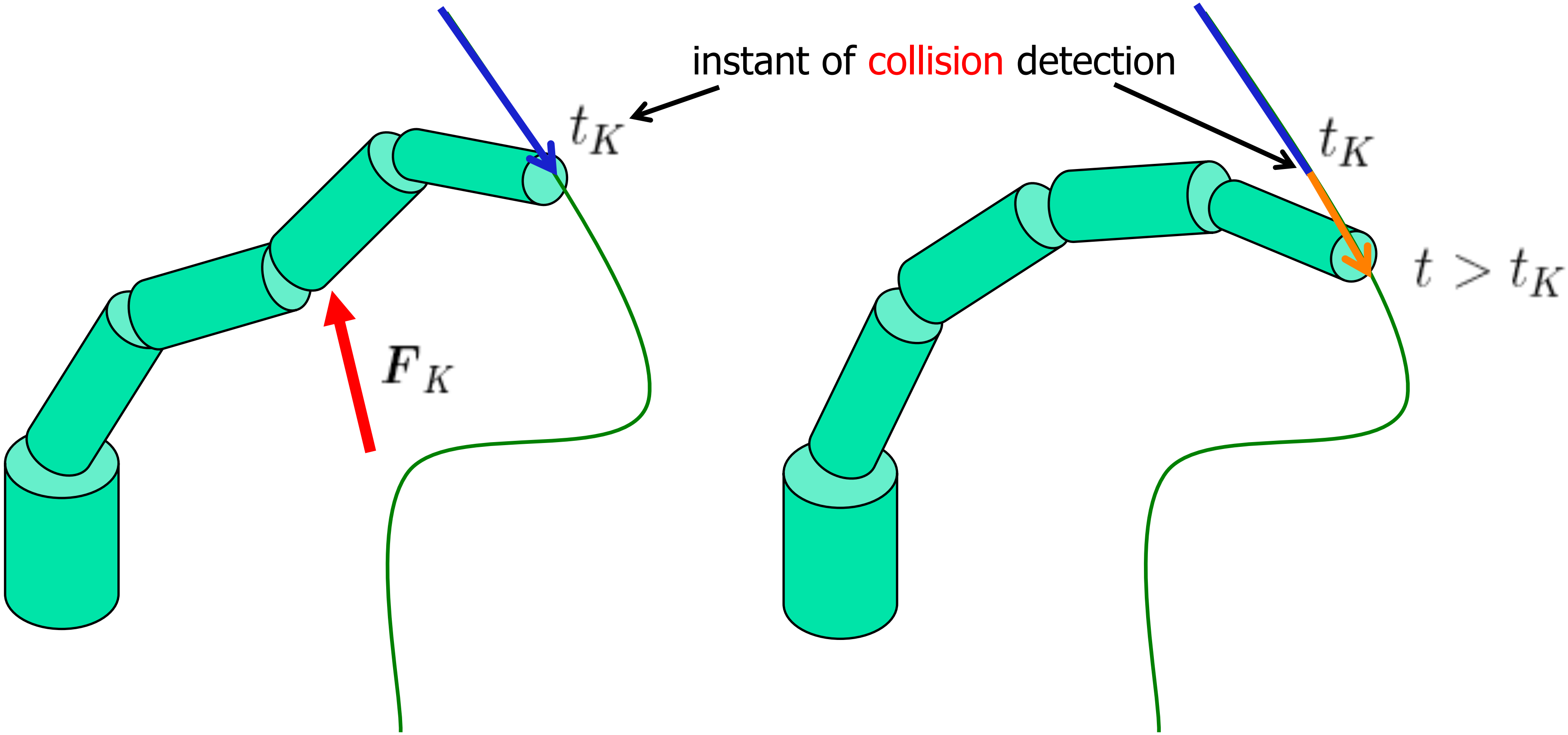
Reaction with time scaling

video



Use of kinematic redundancy

- collision detection ⇒ robot reacts so as to preserve as much as possible (and if possible at all) execution of the planned Cartesian trajectory for the end-effector



Task kinematics

- task coordinates $x \in \mathbf{R}^m$ 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 (at a given robot state)

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

arbitrary joint acceleration

Dynamic redundancy resolution

set for compactness $\boldsymbol{n}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$

- all joint torques realizing a precise control of the desired (Cartesian) task

$$\ddot{x}_d + \boldsymbol{K}_P \boldsymbol{e} + \boldsymbol{K}_D \dot{\boldsymbol{e}}$$

$$\begin{aligned}\boldsymbol{\tau} \;=\; & \boldsymbol{M}(\boldsymbol{q})\boldsymbol{G}(\boldsymbol{q})\left[\ddot{\boldsymbol{x}} - \dot{\boldsymbol{J}}(\boldsymbol{q})\dot{\boldsymbol{q}} + \boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q})\boldsymbol{n}(\boldsymbol{q},\dot{\boldsymbol{q}})\right] \\ & + \underbrace{\boldsymbol{M}(\boldsymbol{q})(\boldsymbol{I} - \boldsymbol{G}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q}))\boldsymbol{M}^{-1}(\boldsymbol{q})}_{\text{projection matrix in the dynamic null space of } \boldsymbol{J}}\boldsymbol{\tau}_0\end{aligned}$$

arbitrary joint torque available for reaction to collisions

for any generalized inverse $\boldsymbol{G}$, the joint torque has two contributions: one imposes the task acceleration control, the other does not affect it

Dynamically consistent solution
inertia-weighted pseudoinverse

- the most natural choice for matrix $\boldsymbol{G}$ is to use the dynamically consistent generalized inverse of $\boldsymbol{J}$
- in a dual way, denoting by $\boldsymbol{H}$ a generalized inverse of $\boldsymbol{J}^T$, the joint torques can in fact be always decomposed as

$$\boldsymbol{\tau} = \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{F} + (\boldsymbol{I} - \boldsymbol{J}(\boldsymbol{q})^T\boldsymbol{H}(\boldsymbol{q}))\boldsymbol{\tau}_0$$

- the inertia-weighted choices for $\boldsymbol{H}$ and $\boldsymbol{G}$ are then

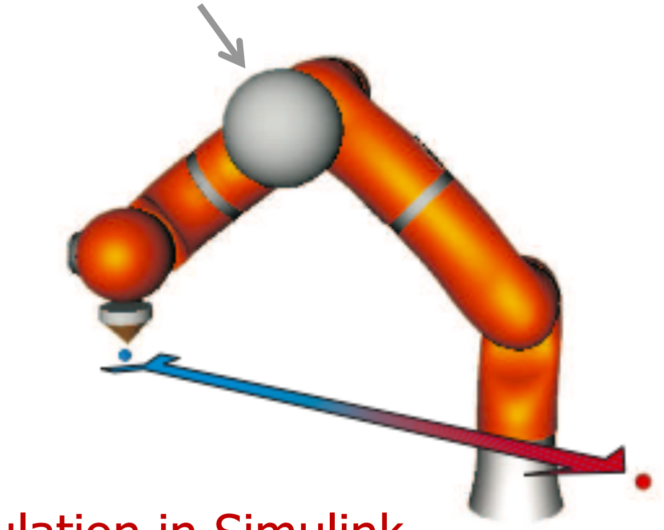
$$\begin{aligned} \boldsymbol{H}_M(\boldsymbol{q}) &= \left(\boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q})\boldsymbol{J}^T(\boldsymbol{q})\right)^{-1}\boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q}) \\ &=: \boldsymbol{\Lambda}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q}), \end{aligned}$$

$$\boldsymbol{G} = \boldsymbol{H}_M^T = \boldsymbol{M}^{-1}\boldsymbol{J}^T\boldsymbol{\Lambda}$$

- thus, the dynamically consistent solution is given by

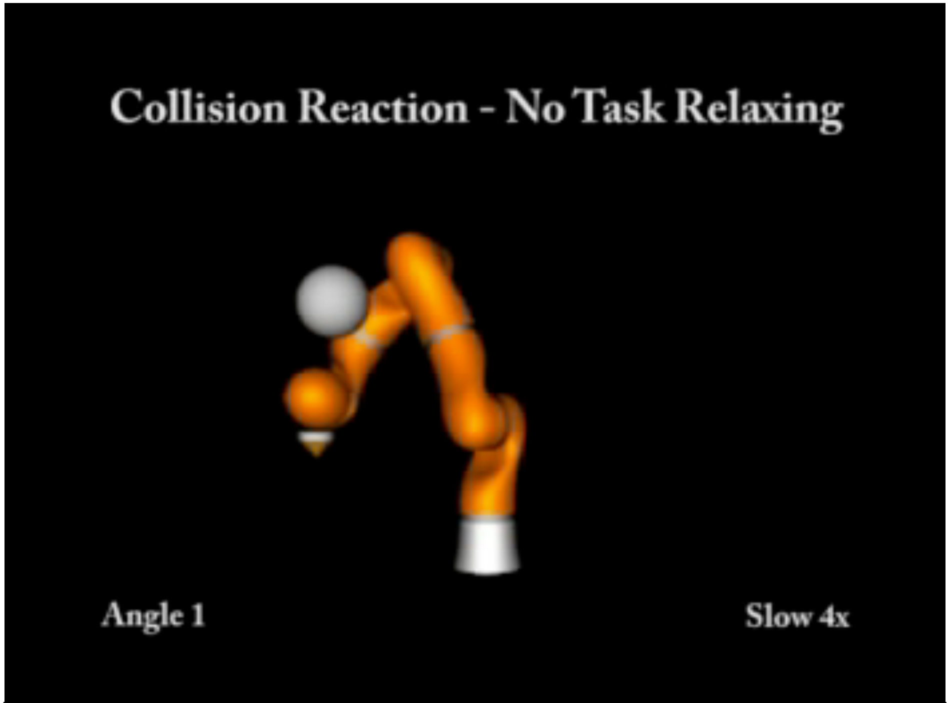
$$\boxed{\begin{aligned} \boldsymbol{\tau} \;=\; & \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{\Lambda}(\boldsymbol{q})(\ddot{\boldsymbol{x}} - \dot{\boldsymbol{J}}(\boldsymbol{q})\dot{\boldsymbol{q}} + \boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q})\boldsymbol{n}(\boldsymbol{q},\dot{\boldsymbol{q}})) \\ & + (\boldsymbol{I} - \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{H}_M(\boldsymbol{q}))\boldsymbol{\tau}_0 \end{aligned}}$$

Cartesian task preservation



simulation in Simulink
visualization in VRML

video



De Luca, Ferrajoli @IROS 2008

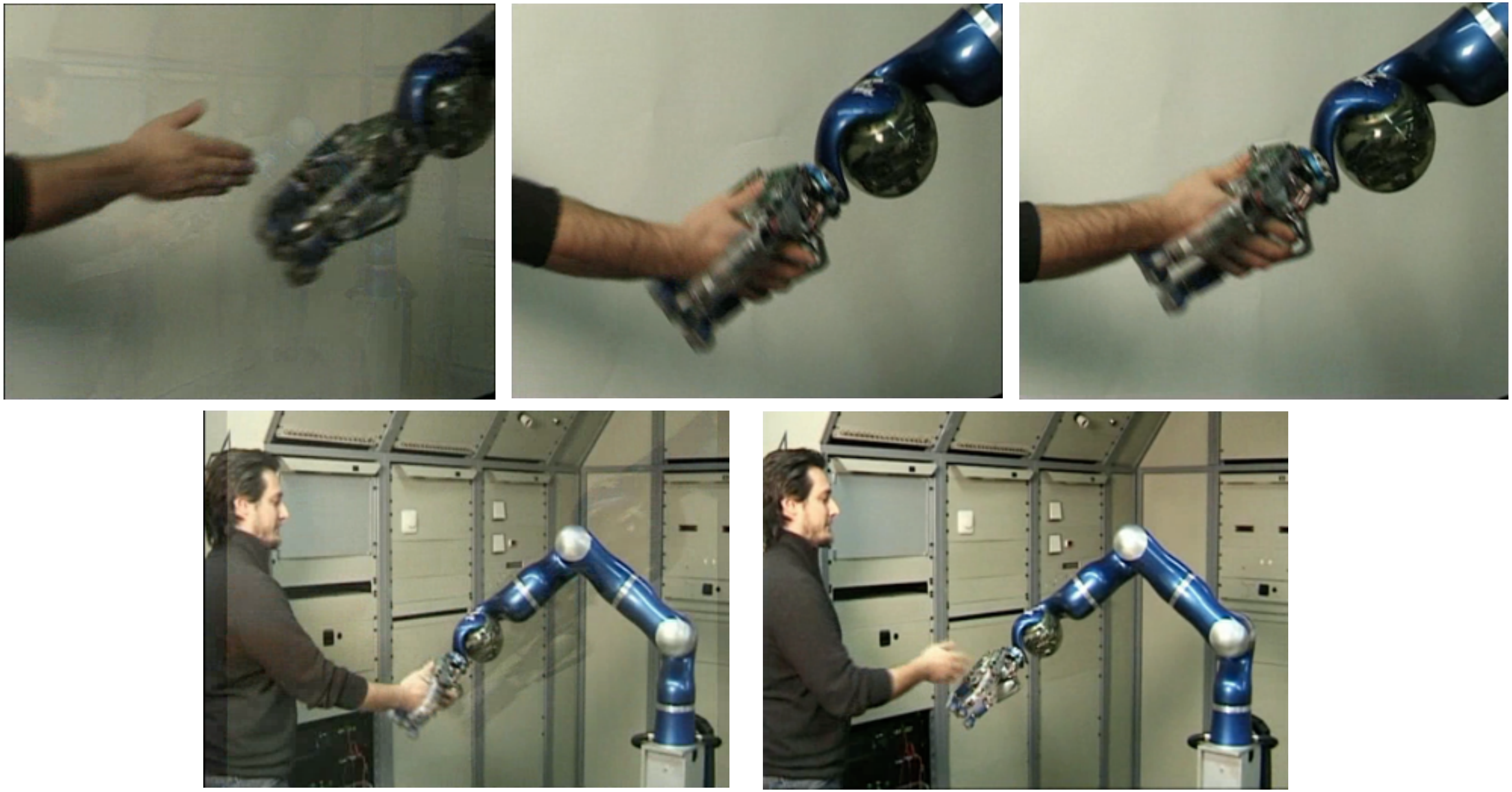
- wish to preserve the whole Cartesian task (end-effector position & orientation) reacting to collisions by using only self-motions in the joint space
- if the residual ($\propto$ contact force) grows too large, orientation is relaxed first and then, if necessary, the full task is abandoned (priority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

Cartesian task preservation
Experiments with LWR4+ robot

video @IROS 2017

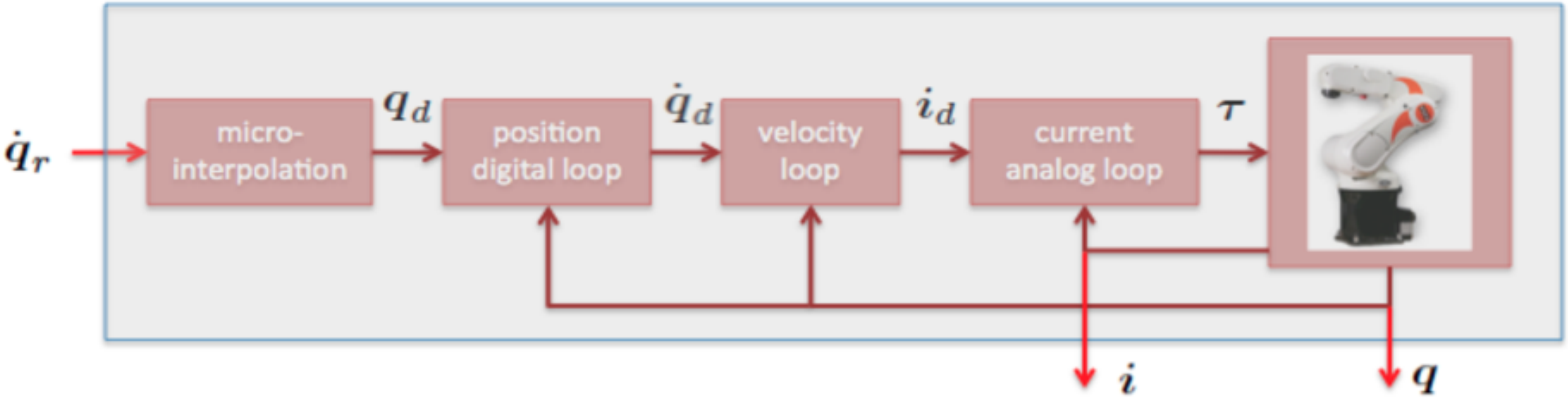
idle ⇔ relax ⇔ abort

Combined use
6D F/T sensor at the wrist + residuals

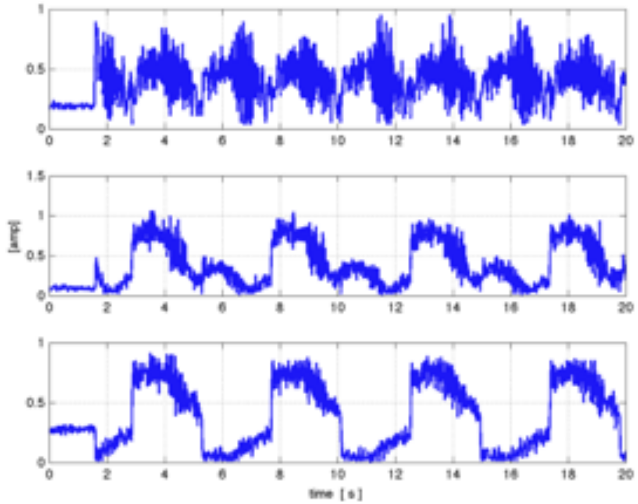


- enables easy distinction of intentional interactions vs. unexpected collisions
- it is sufficient to include the F/T measure in the expression of the residual!

HRI/HRC in closed control architectures
KUKA KR5 Sixx R650 robot



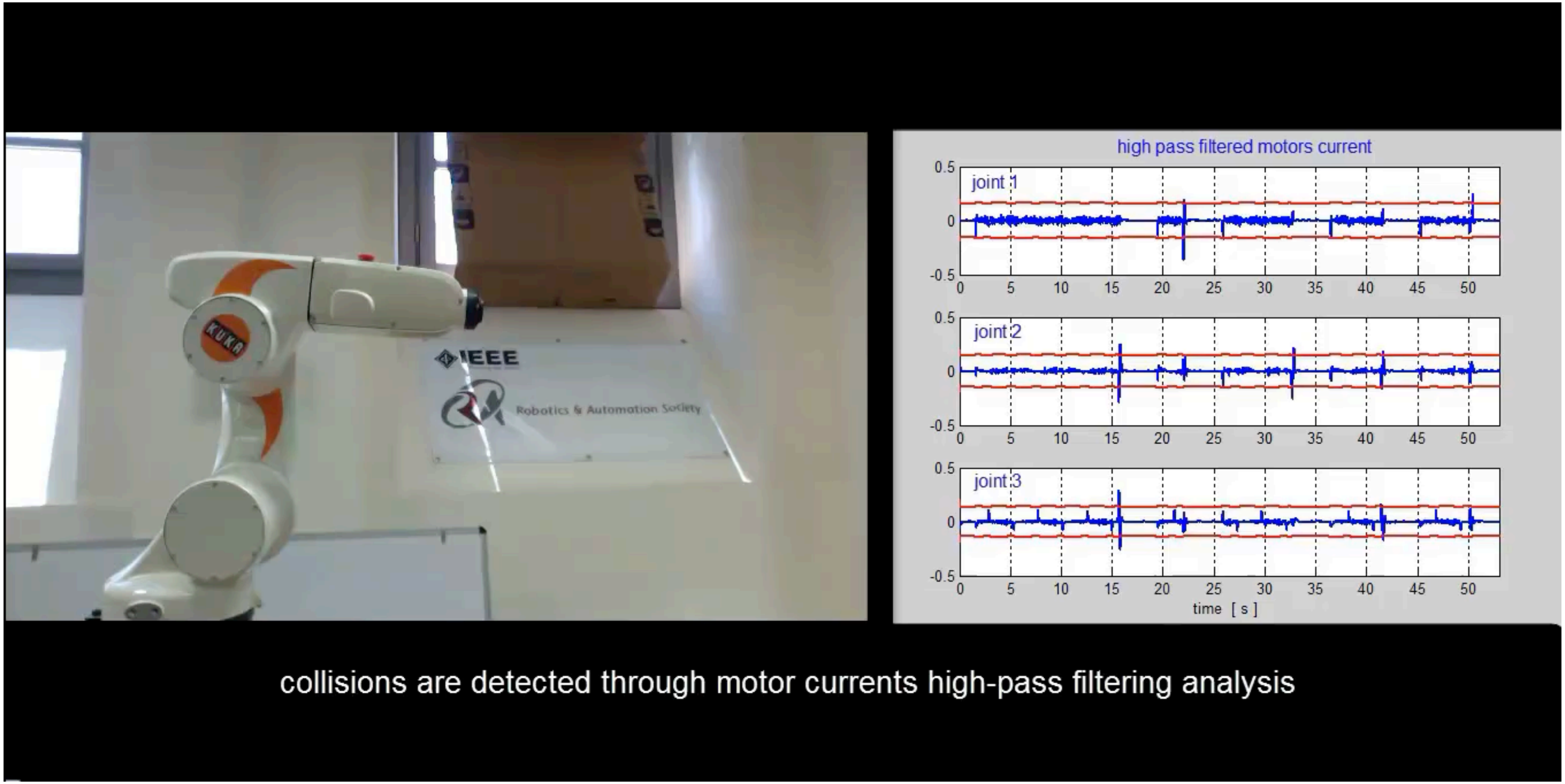
- low-level control laws are not known nor accessible by the user: no current or torque commands can be used
- user programs, based also on other exteroceptive sensors (vision, Kinect, F/T sensor) can be implemented on an external PC via the RSI (RobotSensorInterface), communicating with the KUKA controller every 12 ms
- robot measures available to the user: joint positions (by encoders) and [absolute value of] motor currents
- controller reference is given as a velocity or a position in joint space (also Cartesian commands are accepted)



motor currents measured on first three joints

Collision detection and stop

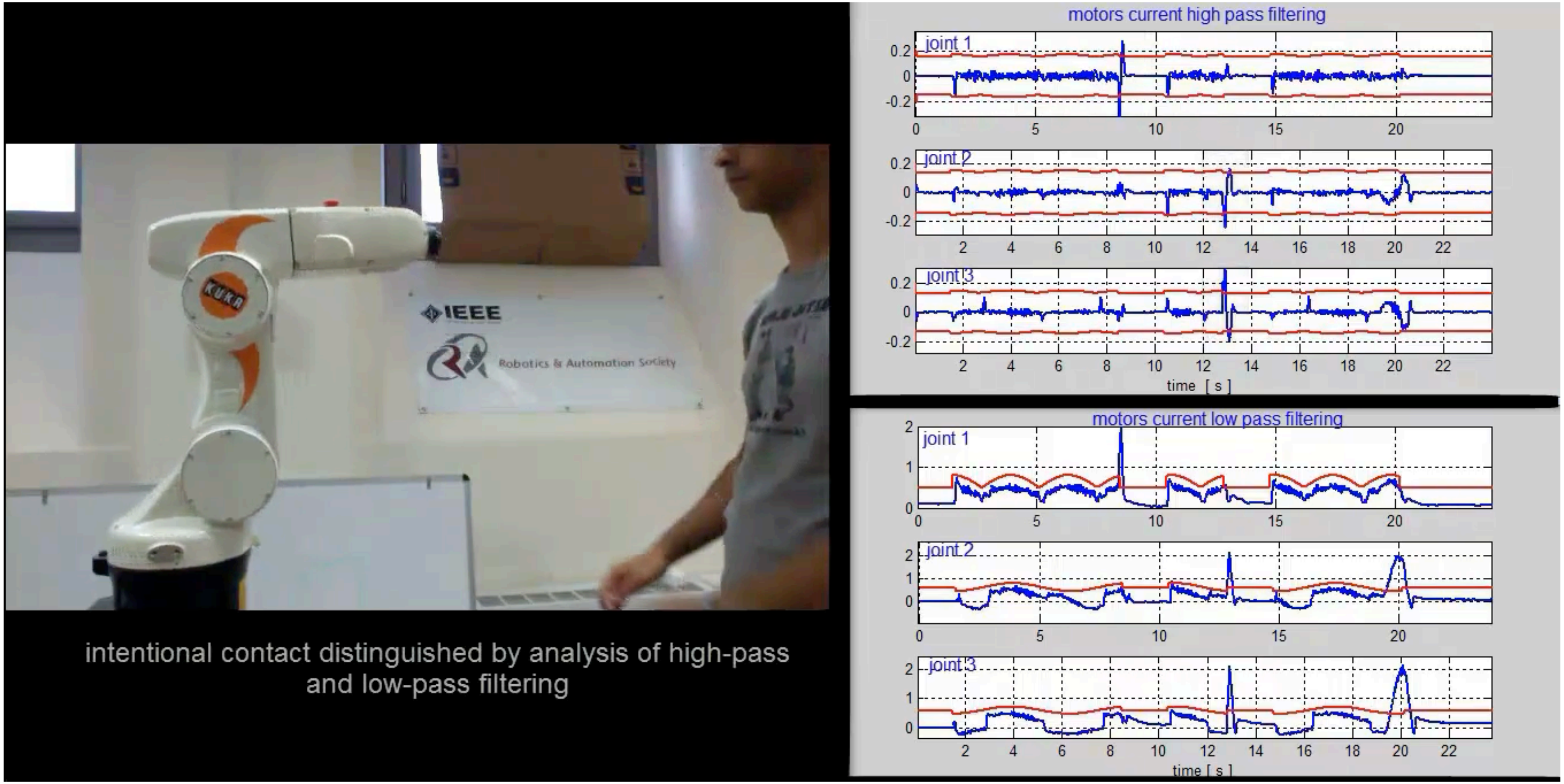
video @ICRA 2013



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

Distinguish accidental collisions from intentional contact and then collaborate

video @ICRA 2013



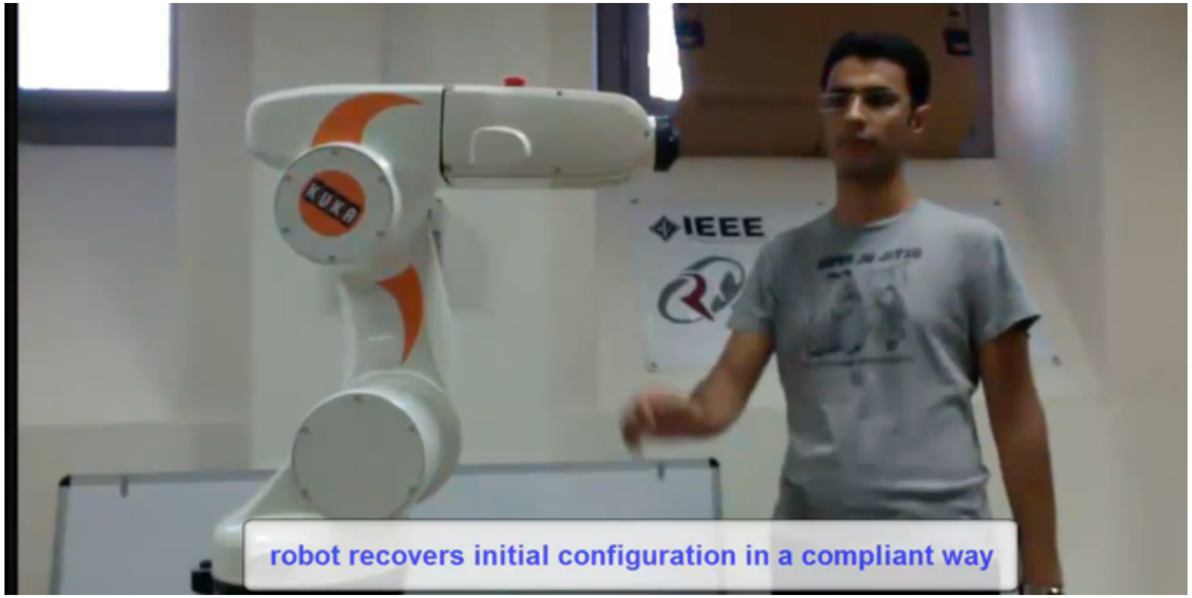
with both high-pass and low-pass filtering of motor currents
– here collaboration mode is manual guidance of the robot

Other possible robot reactions after collaboration mode is established

collaboration mode:
pushing/pulling
the robot

video
@ICRA
2013

collaboration mode:
compliant-like
robot behavior



video
@ICRA
2013

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