Robotics 2

Collision detection and robot reaction

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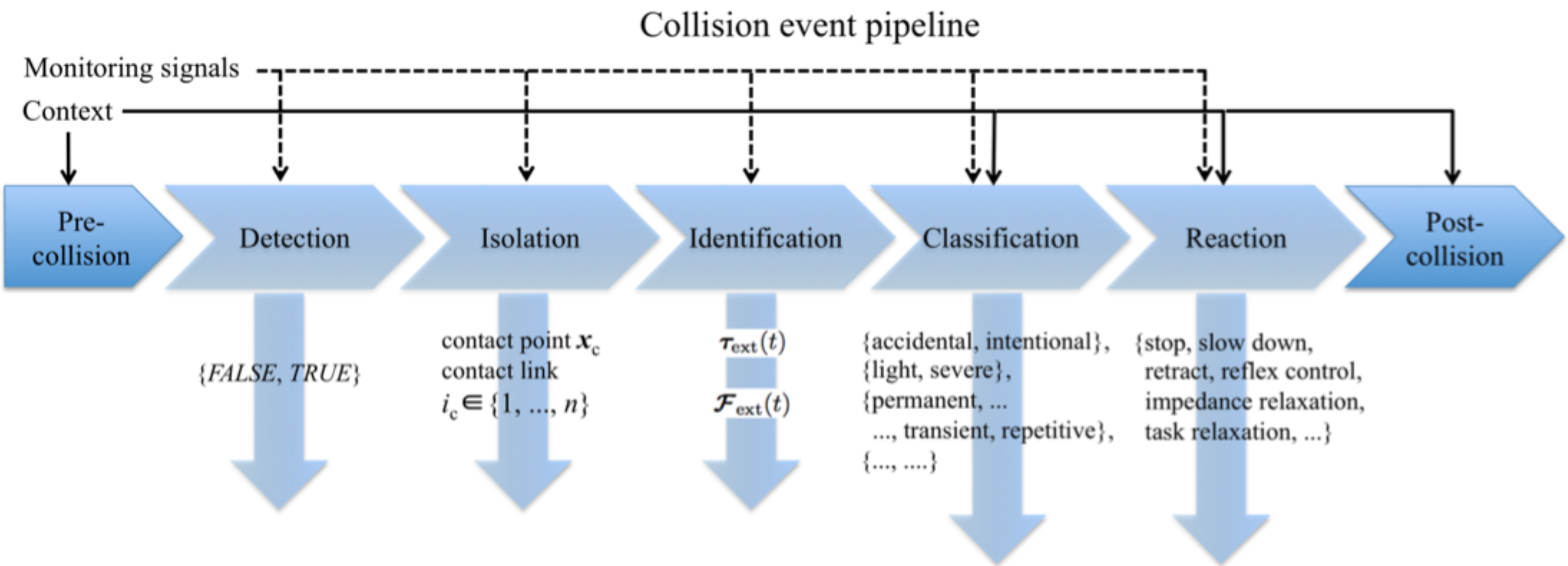
Handling of robot collisions

- safety in physical Human-Robot Interaction (pHRI)
- robot dependability (i.e., beyond reliability)
  - mechanics: lightweight construction and inclusion of compliance
  - 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, detect and react to collisions
  - possibly, using only robot proprioceptive sensors
- phases: pre-impact, impact and post-impact

PHRIENDS: FP6 STREP European project (2006-09) → FP7 IP European project (2011-15): SAPHARI

SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction

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)
- allow 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

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

  - based on robot state and numerical estimate of acceleration

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

  - based on the parallel simulation of robot dynamics

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

- 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!)

joint torque caused by link collision

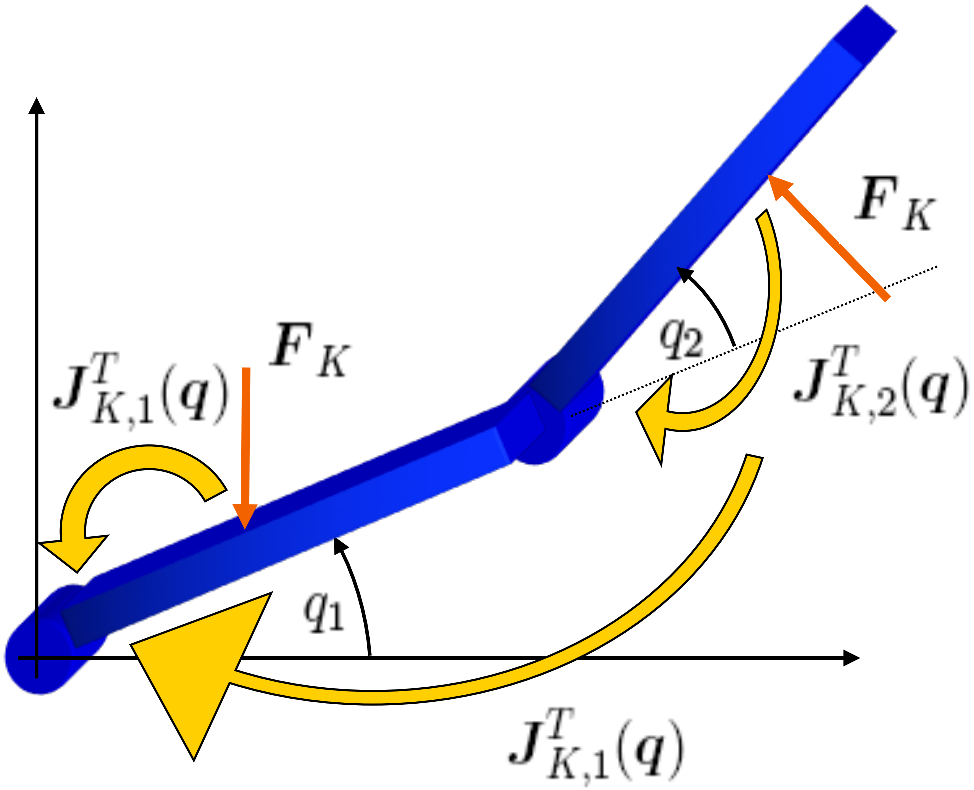
$$\boxed{\tau_K = J_K^T(q) F_K}$$

transpose of the Jacobian associated to the contact point/area

- collisions may occur at any (unknown) location along the whole robotic structure
- simplifying assumptions (not strictly needed)
  - single contact/collision
  - manipulator as an open kinematic chain

Analysis of a collision

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



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

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

Relevant dynamic properties

- total energy and its variation

$$E = T + U = \frac{1}{2}\dot{q}^T M(q)\dot{q} + U_g(q) \qquad \boxed{\dot{E} = \dot{q}^T \tau_{\text{tot}}}$$

- generalized moments and their decoupled dynamics

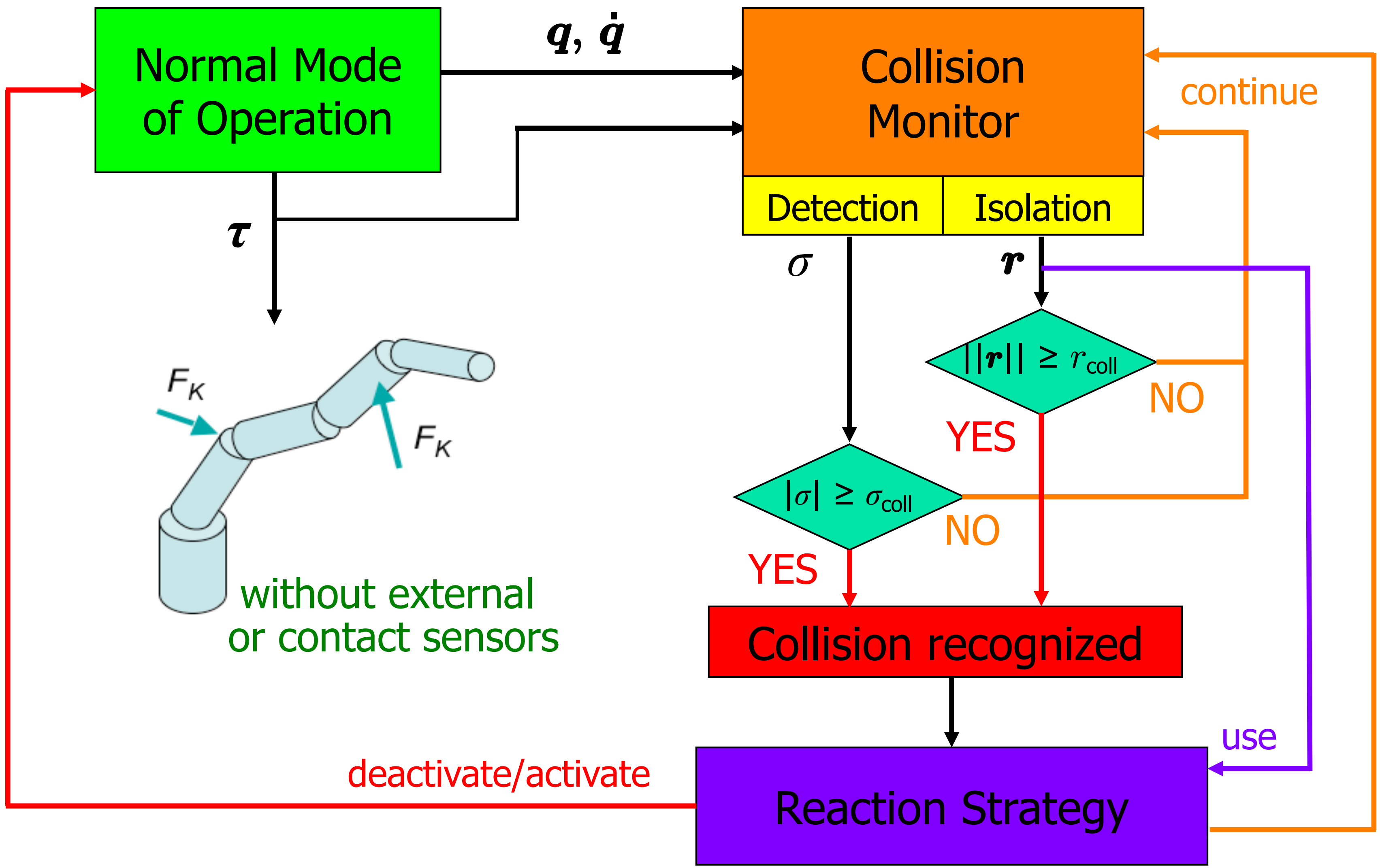
$$p = M(q)\dot{q}$$

$$\dot{p} = \tau_{\text{tot}} + S^T(q,\dot{q})\dot{q} - g(q)$$

NOTE: it is the vector version of the formula encountered for actuator FDI

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

Monitoring collisions



Energy-based detection of collisions

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

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

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

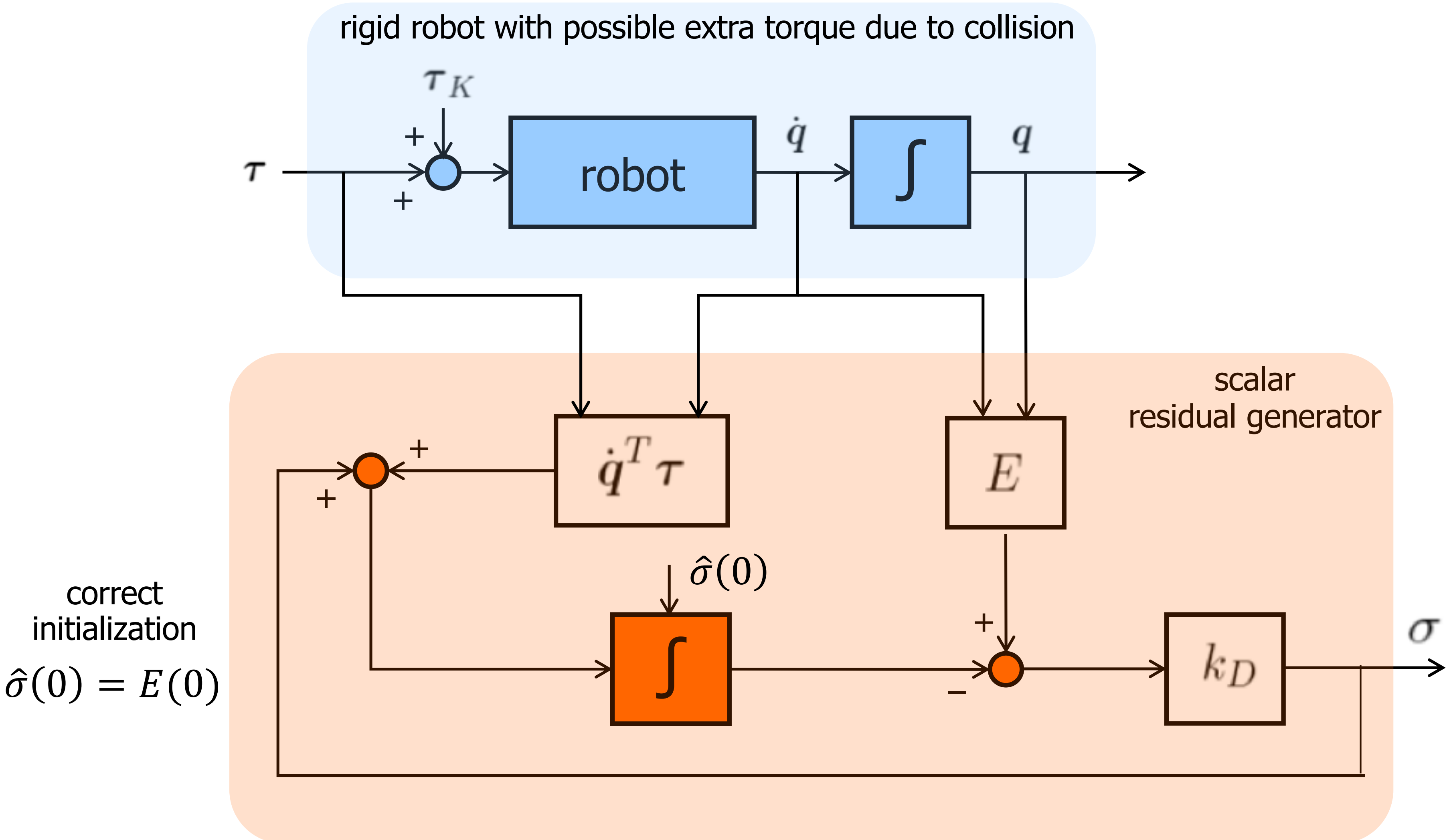
- … and its dynamics (needed only for analysis)

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

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

Block diagram of residual generator

energy-based scalar signal



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

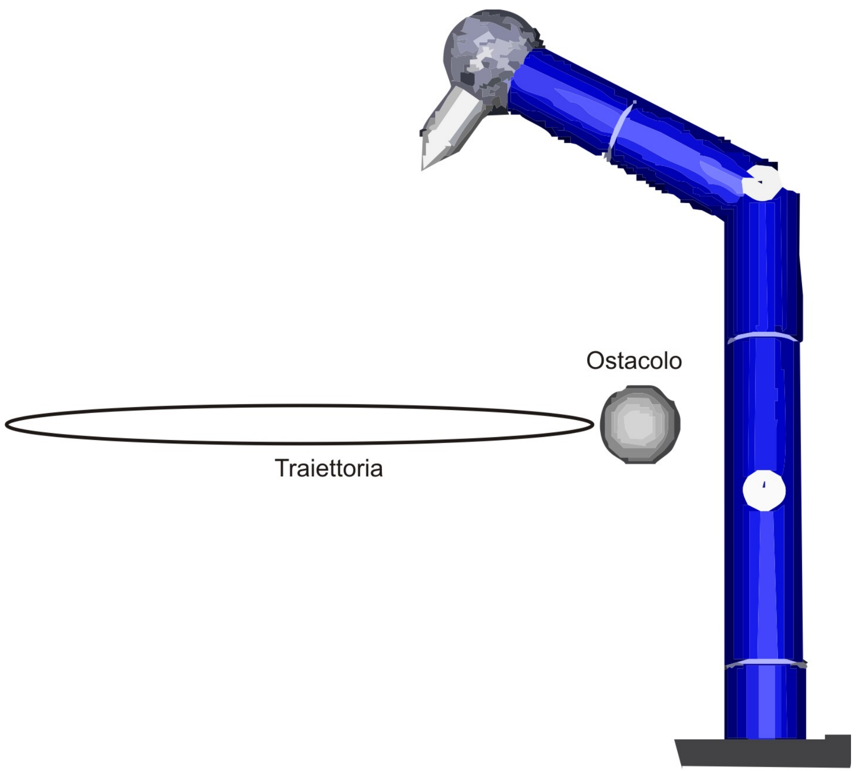
Analysis of the energy-based method

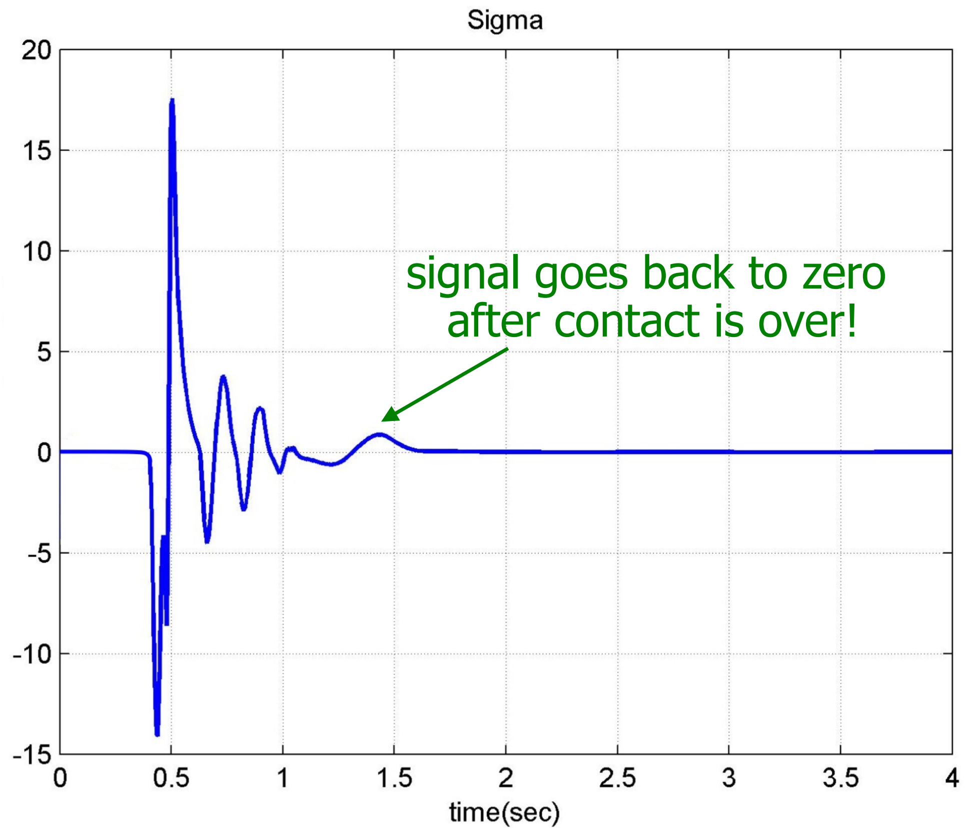
- very simple scheme (scalar signal)
- it can only detect the presence of collision forces/torques (wrenches) that produce work on the linear/angular velocities (twists) at the contact
- does not work when the robot stands still…

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

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

Collision detection
simulation with a 7R robot

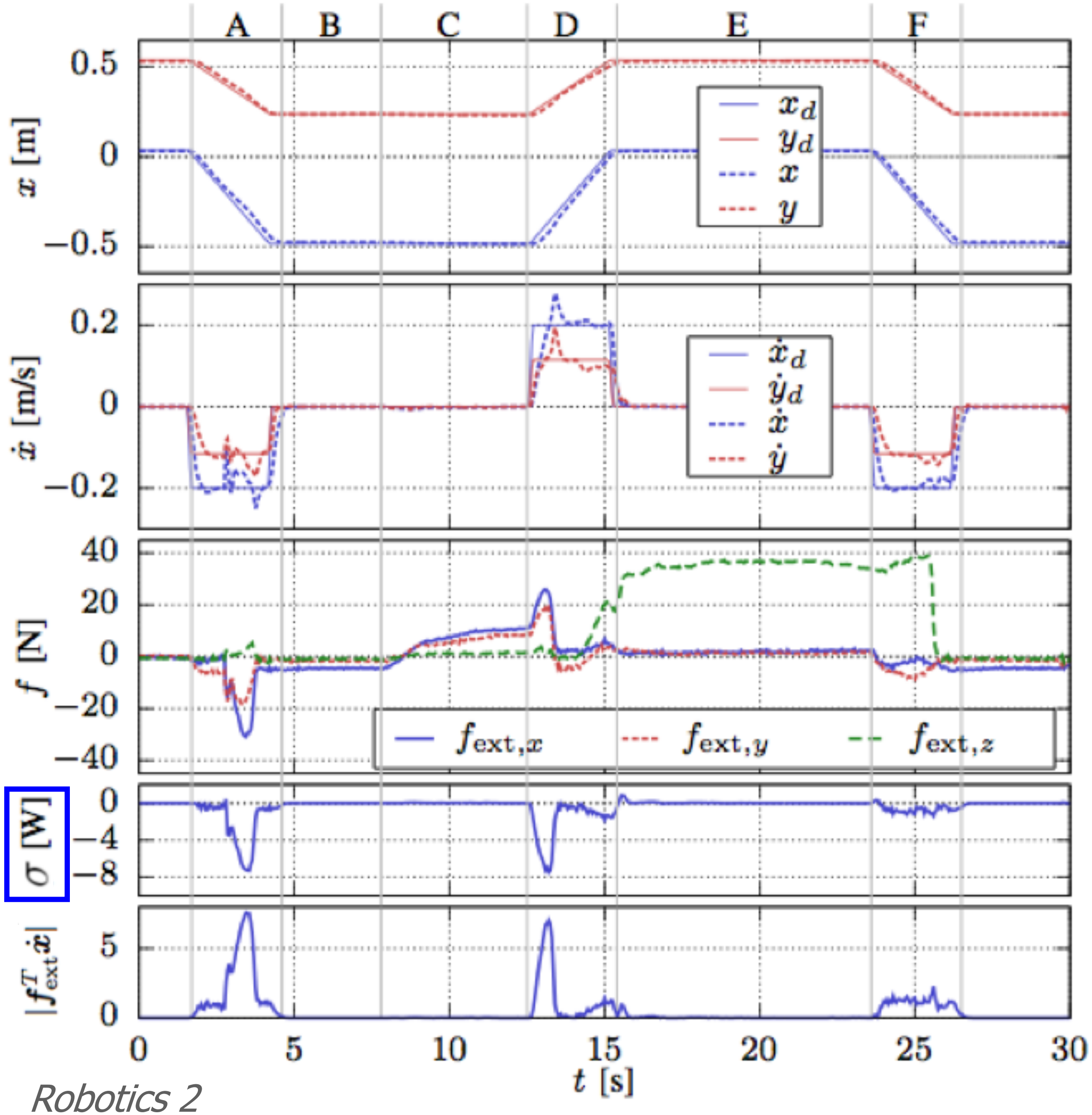




detection of a collision with a fixed obstacle in the work space during the execution of a Cartesian trajectory (redundant robot)

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...)

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

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

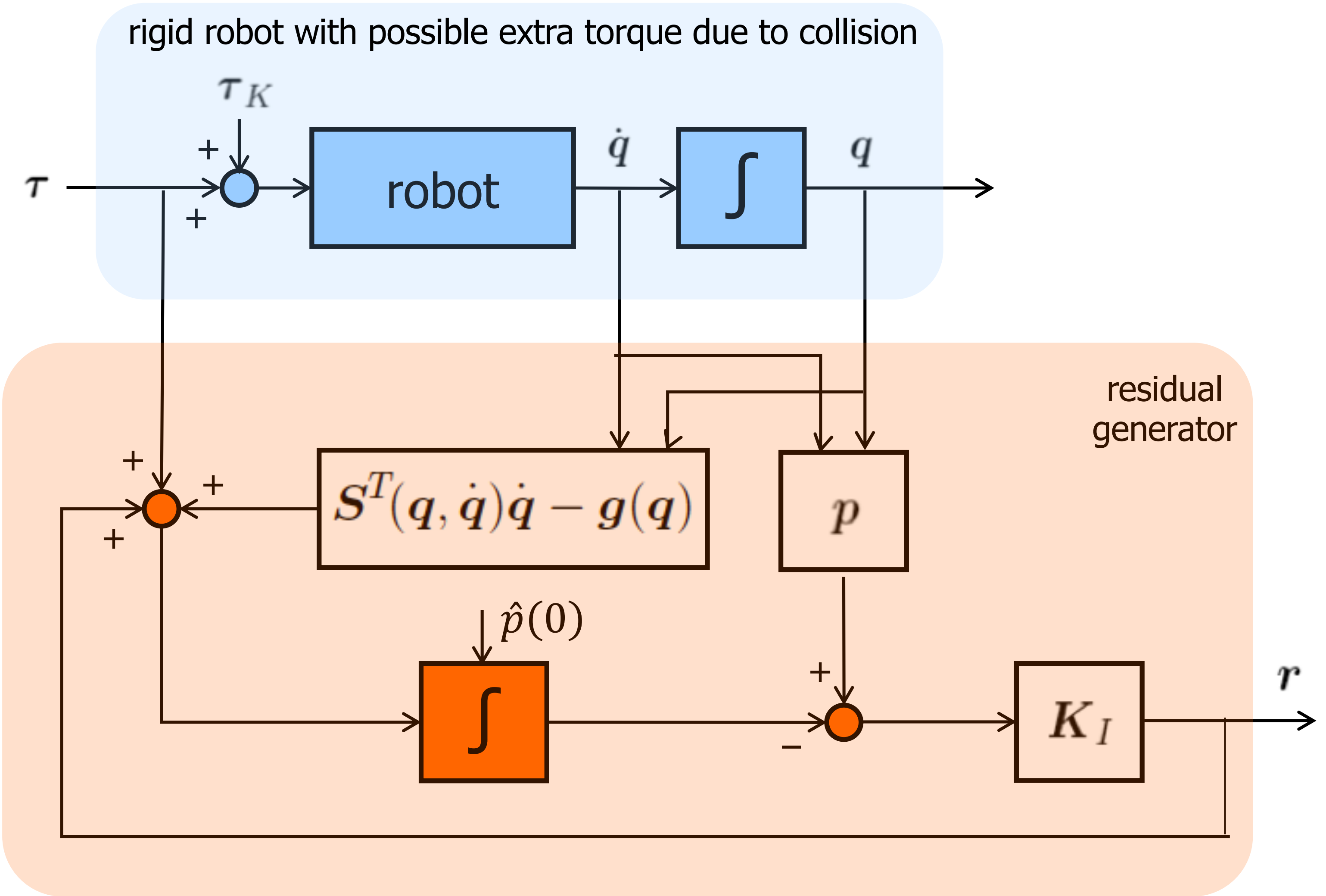
- ... and its decoupled dynamics

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

N 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)

Block diagram of residual generator

momentum-based vector signal



correct initialization
$\hat{p}(0) = p(0)$

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

Analysis of the momentum method

- ideal situation (no noise/uncertainties)

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

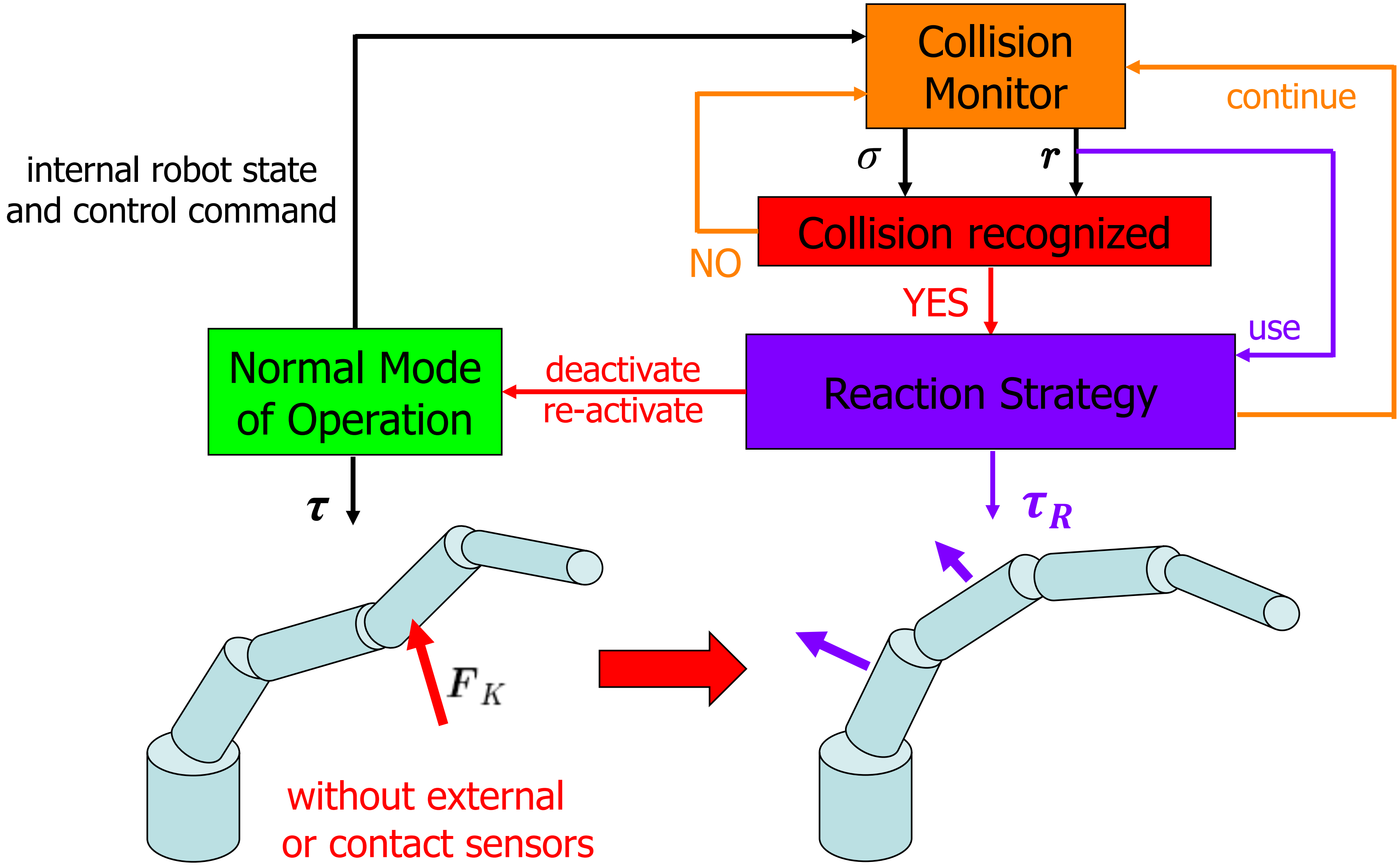
- isolation property: collision has occurred in an area located up to the i-th link if

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

$$\begin{matrix} \uparrow & & \uparrow \\ i+1 & \dots & N \end{matrix}$$

- 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)

Safe reaction to collisions



Robot reaction strategy

- "zero-gravity" control in any operative mode

$$\tau = \tau' + g(q)$$

- upon detection of a collision (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

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

"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, 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 more easily pushed way"

from a cow ...

... to a frog!

DLR LWR-III robot dynamics

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

motor torques commands

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

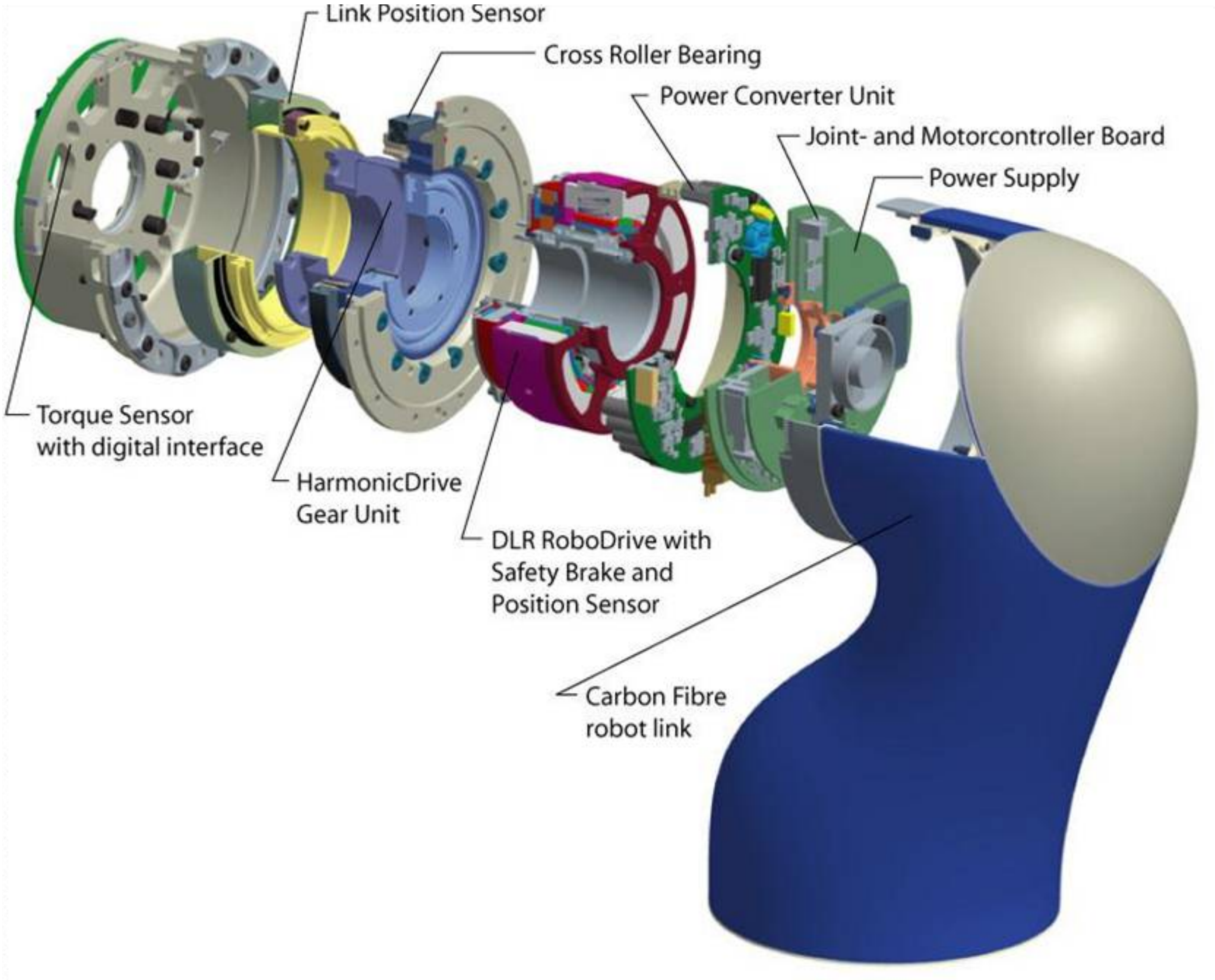
joint torques due to link collision

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

- two 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"

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

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

- the other alternative uses joint position and velocity measures at the motor and link sides and still the commanded torque
- motion control laws are more complex when joint elasticity is present
- 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

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

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

motor position

link position

(diagonal) matrix of joint stiffness

Reaction strategies
specific for elastic joint robots

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

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

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

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

- 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

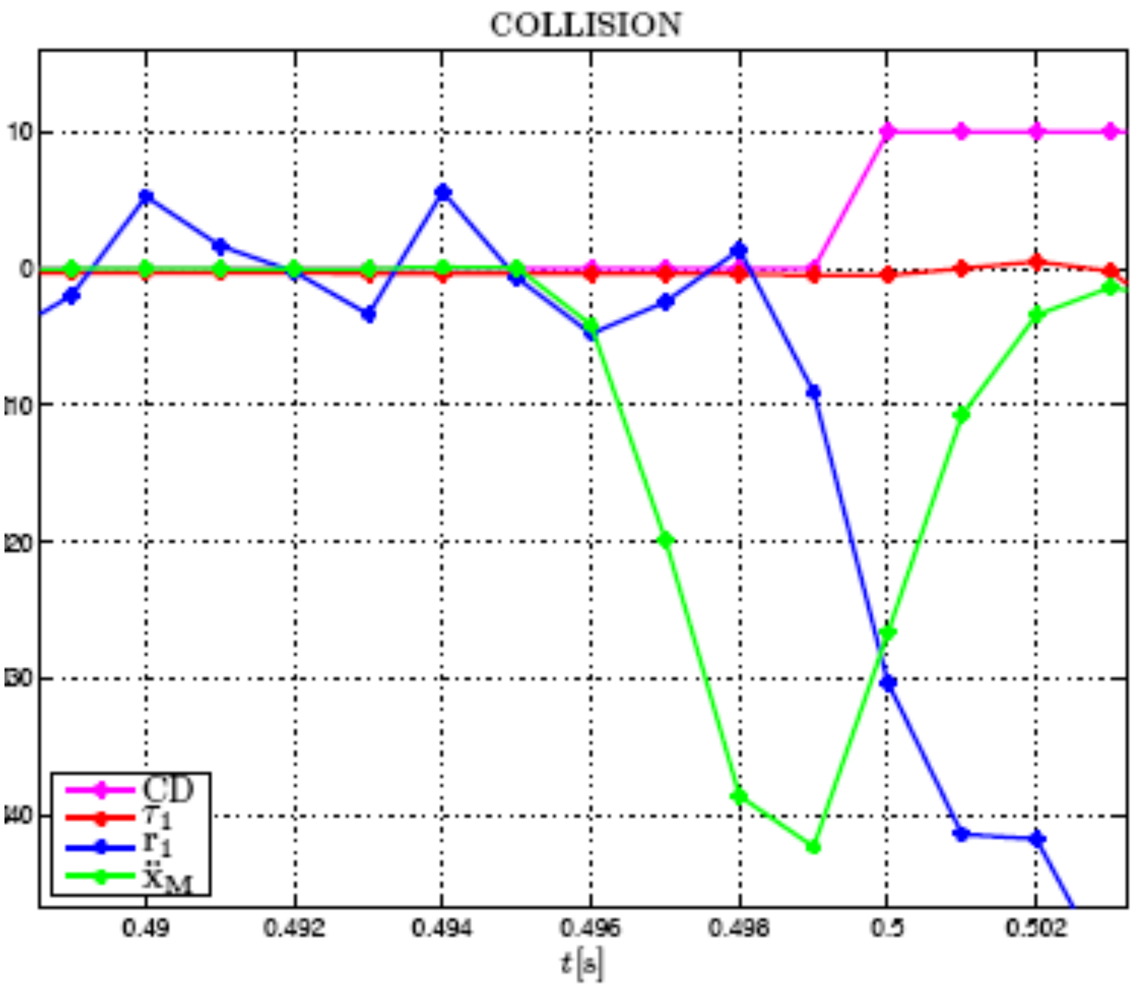
strategy 0: no reaction

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 quite immediately

Delay in collision detection



2-4 msec!

impact with the dummy head

measured (elastic) joint torque

residual r_1

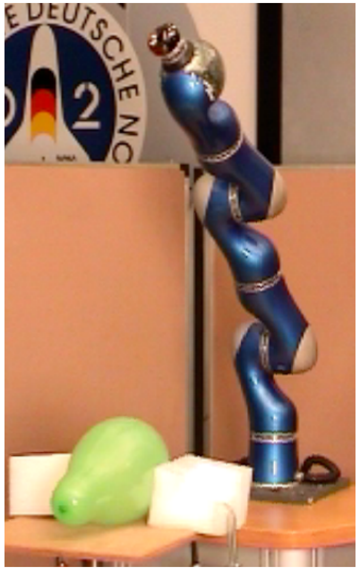
0/1 index for detection

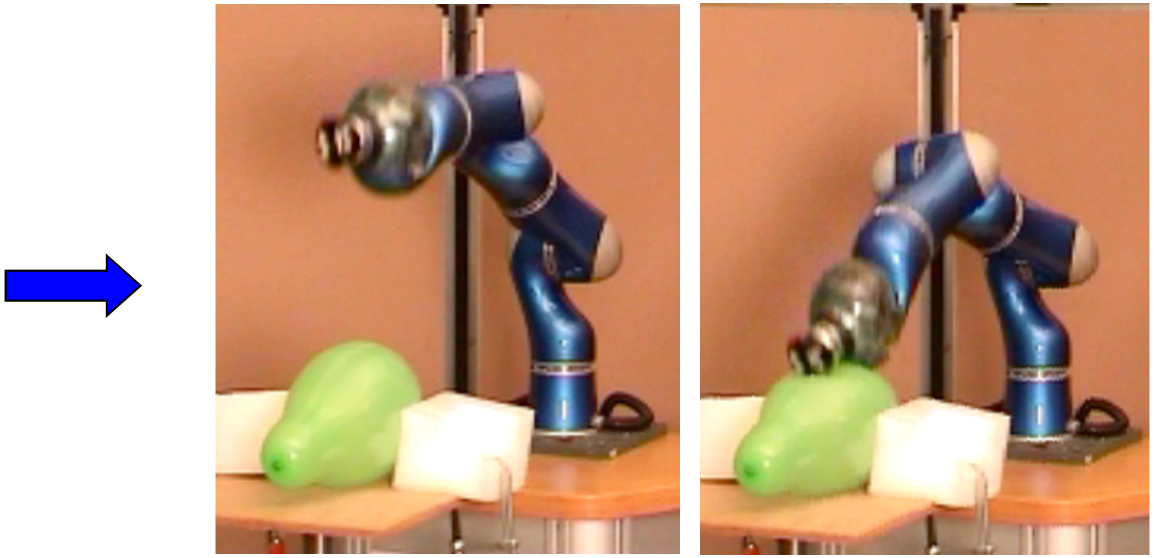
dummy head acceleration

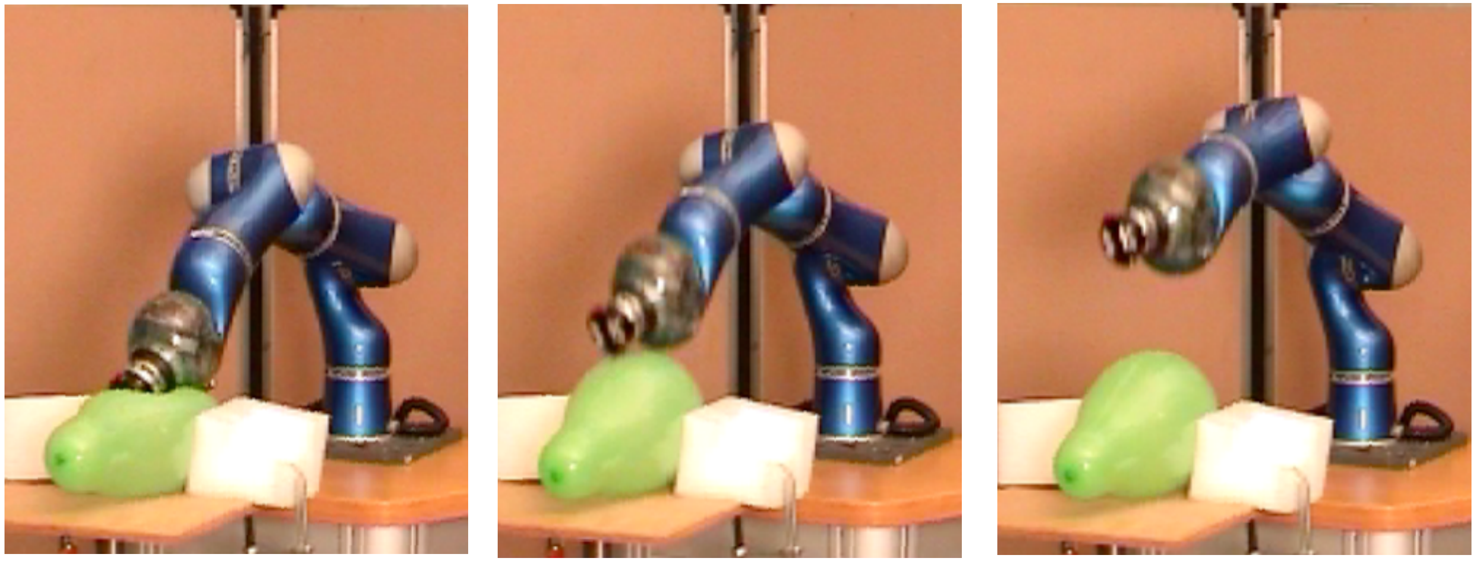
gain K_I = diag{25}

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

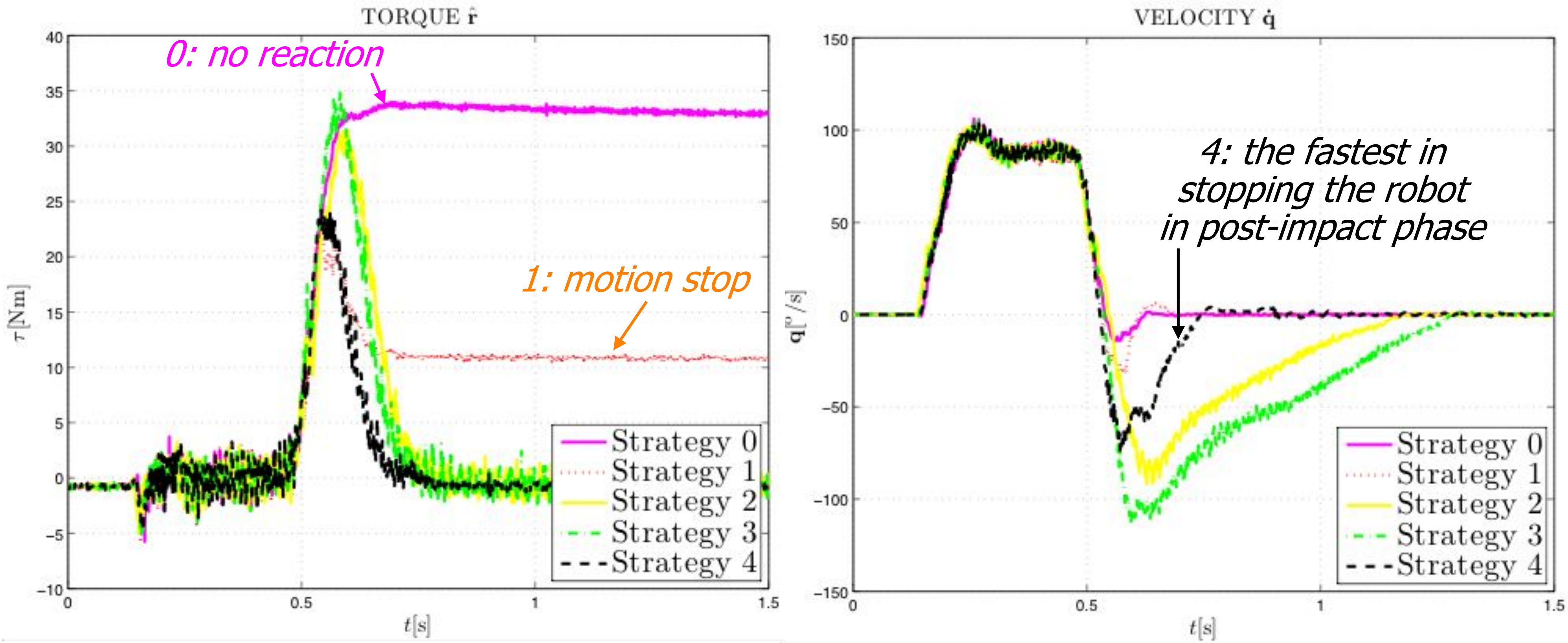
video

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)

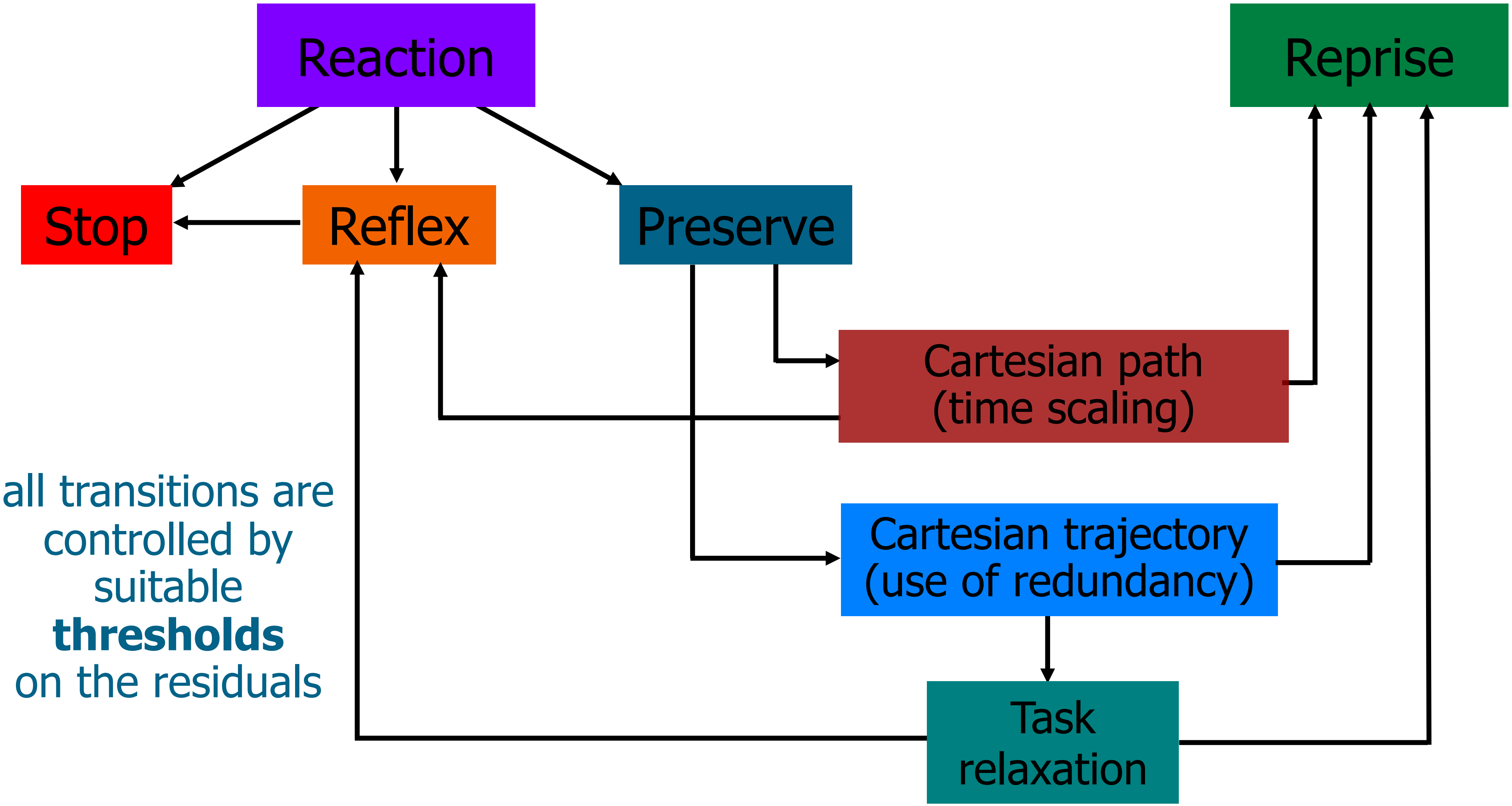
- first impact @90^o/sec

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

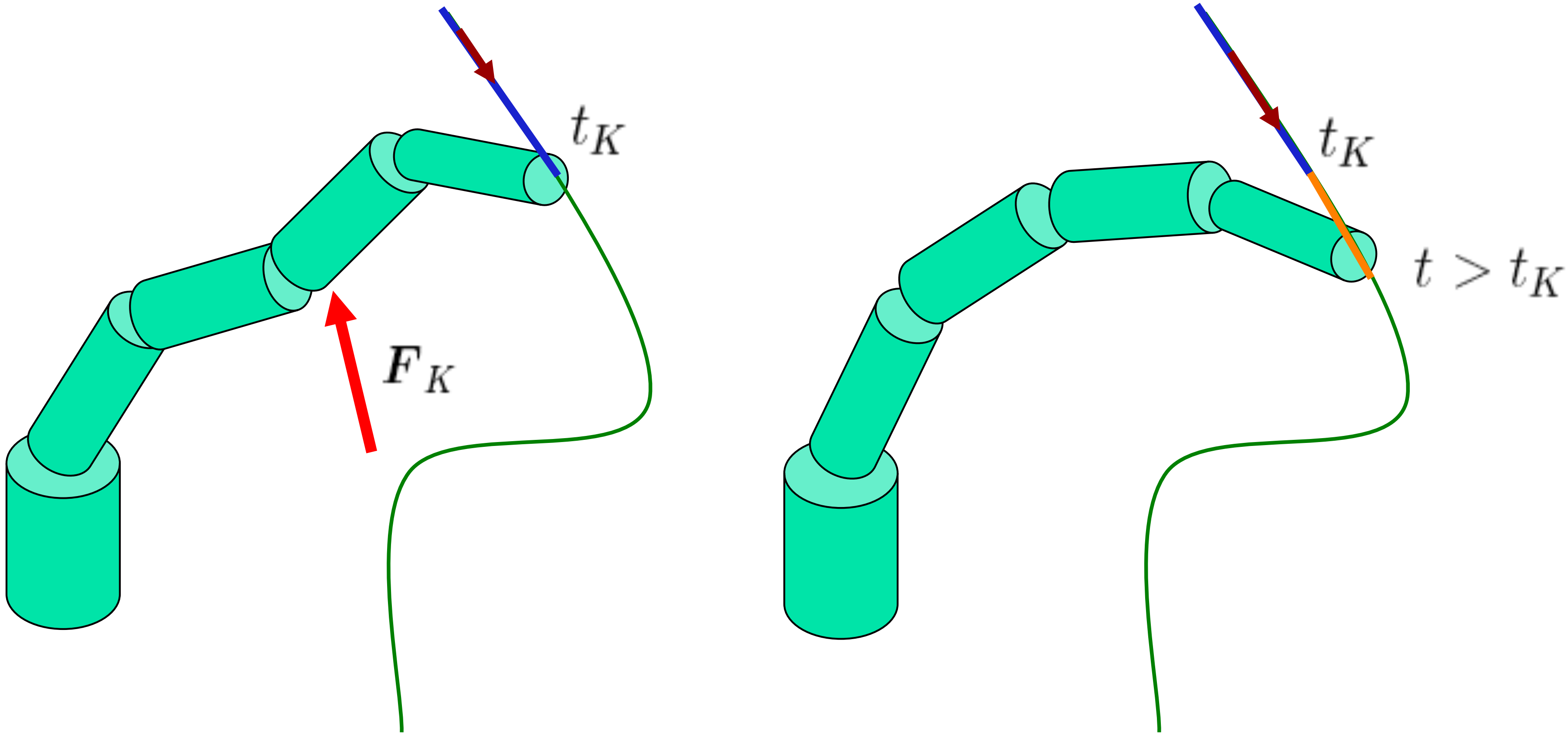
- robot is position-controlled (on a given geometric path)
- timing law slows down, stops, possibly reverses (and then reprises)

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

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

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

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

Dynamically consistent (inertia-weighted) redundancy resolution

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

$$\tau = J^T(q)F + (I - J(q)^T H(q))\tau_0$$

- the inertia-weighted choices for H and G are then

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

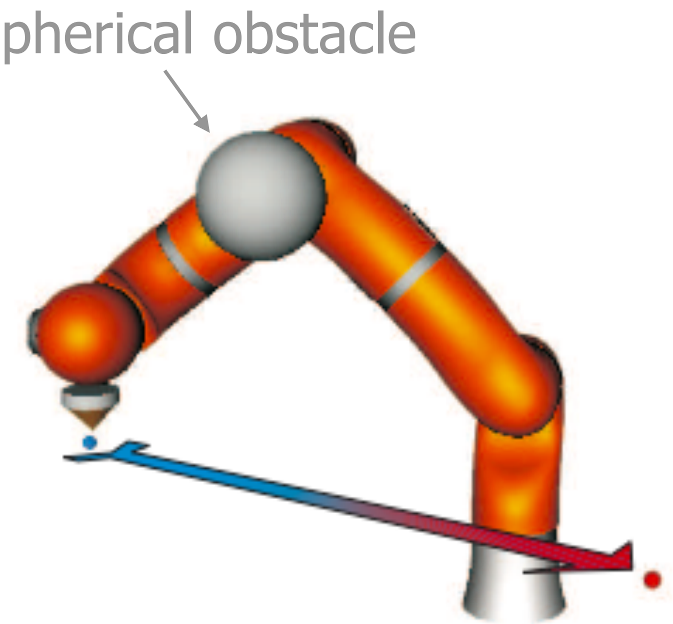
$$G = H_M^T = M^{-1}J^T\Lambda$$

- thus, the dynamically consistent solution is given by

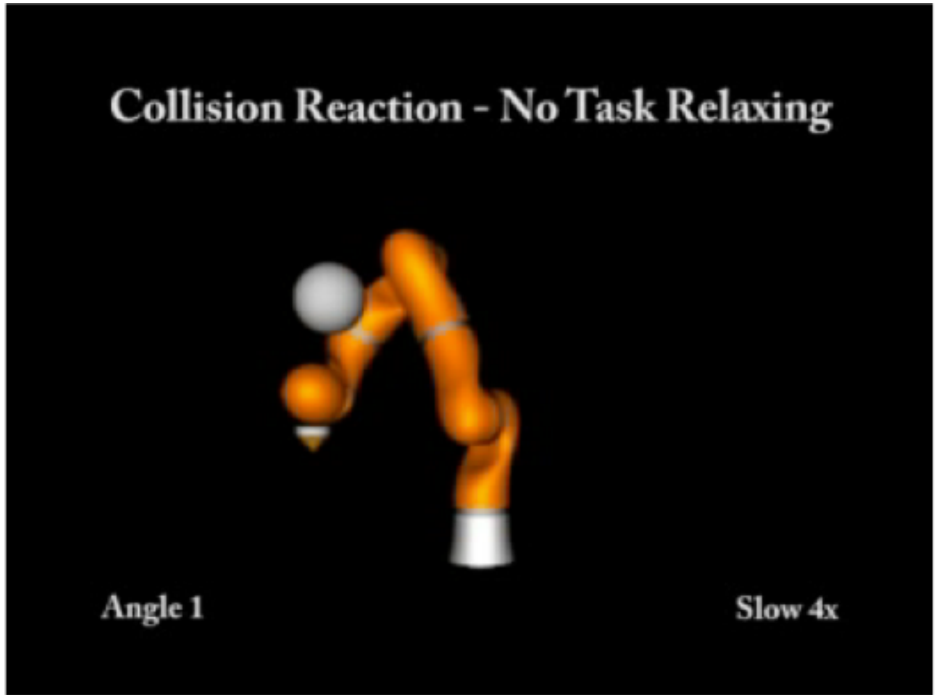
$$\boxed{\begin{aligned} \tau &= J^T(q)\Lambda(q)(\ddot{x} - \dot{J}(q)\dot{q} + J(q)M^{-1}(q)n(q,\dot{q})) \\ &\quad + (I - J^T(q)H_M(q))\tau_0 \end{aligned}}$$

Cartesian task preservation

video



simulation in Simulink
visualization in VRML



De Luca, Ferrajoli: IROS 2008

- wish to preserve the whole Cartesian task (end-effector motion in position/orientation), by reacting to collisions 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)

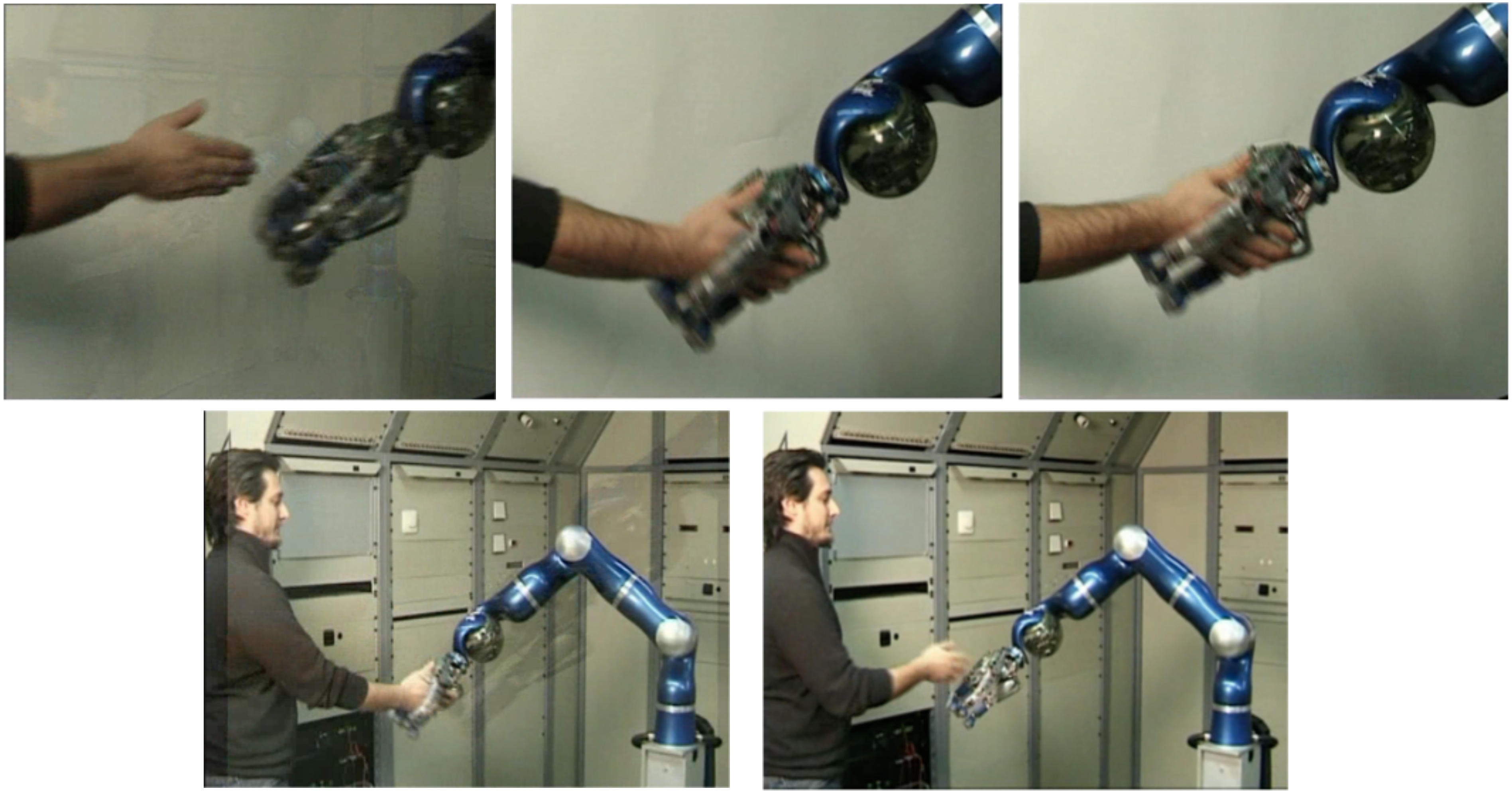
Cartesian task preservation

Experiments with LWR4+ robot

video

idle ⇔ relax ⇔ abort

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



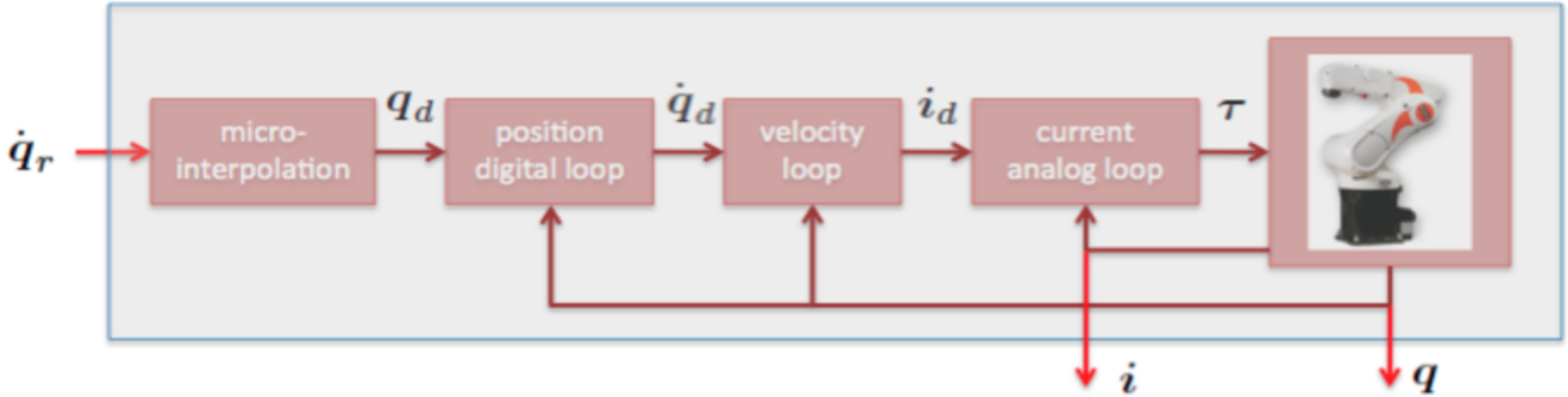
- enables easy distinction of intentional interactions vs. unexpected collisions
- it is sufficient to include the F/T measure in the expression of the residual!

Further research results
obtained within the EU FP7 SAPHARI project

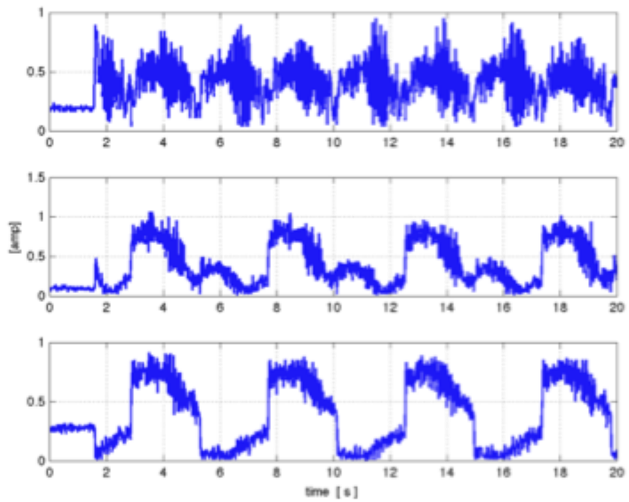
- integrated control approach with
  - collision avoidance (using exteroceptive sensors)
  - collision detection (with the presented methods, if avoidance fails)
  - collision reaction (not limited to retracting the robot from contact areas)
- distinguish intentional contact from unexpected collision without F/T sensor
  - more general types of contacts (at any location, not just at the end-effector)
- understanding human intentions of motion
  - gesture recognition and classification
  - incremental learning of motion/interaction primitives (kinesthetic teaching)
- Human-Robot Collaboration (HRC)
  - search/detect an intentional contact
  - keep the contact while regulating exchanged forces (without force sensing) *or*
  - impose a generalized human-robot impedance behavior at the contact
- portfolio of complex reactive actions to perform HRC in a robust way
  - sequencing of tasks, monitoring progress, switching control laws in real time

HRC under closed control architecture

KUKA KR5 Sixx R650 robot



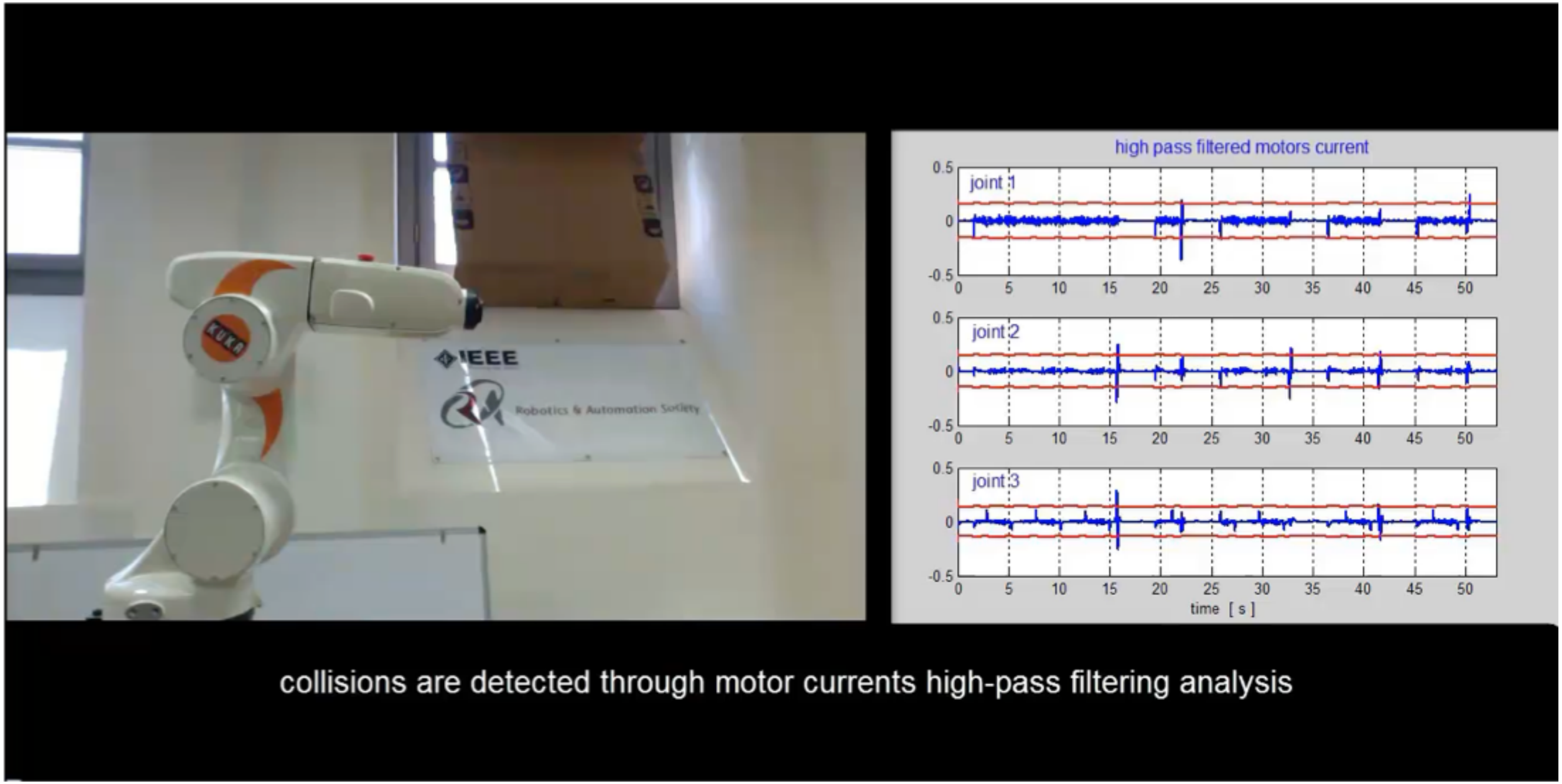
- low-level motor control laws are not known nor accessible by the user
- user programs, based also on other exteroceptive sensors (vision, Kinect, F/T sensor) can be implemented on an external PC via the RSI (RobotSensorInterface), communicating with the KUKA controller every 12 ms
- available robots measures: joint positions (by encoders) and (absolute value of) applied motor currents
- controller reference is given as a velocity or a position in joint space (also Cartesian commands are accepted)



typical motor currents on first three joints

Collision detection and stop

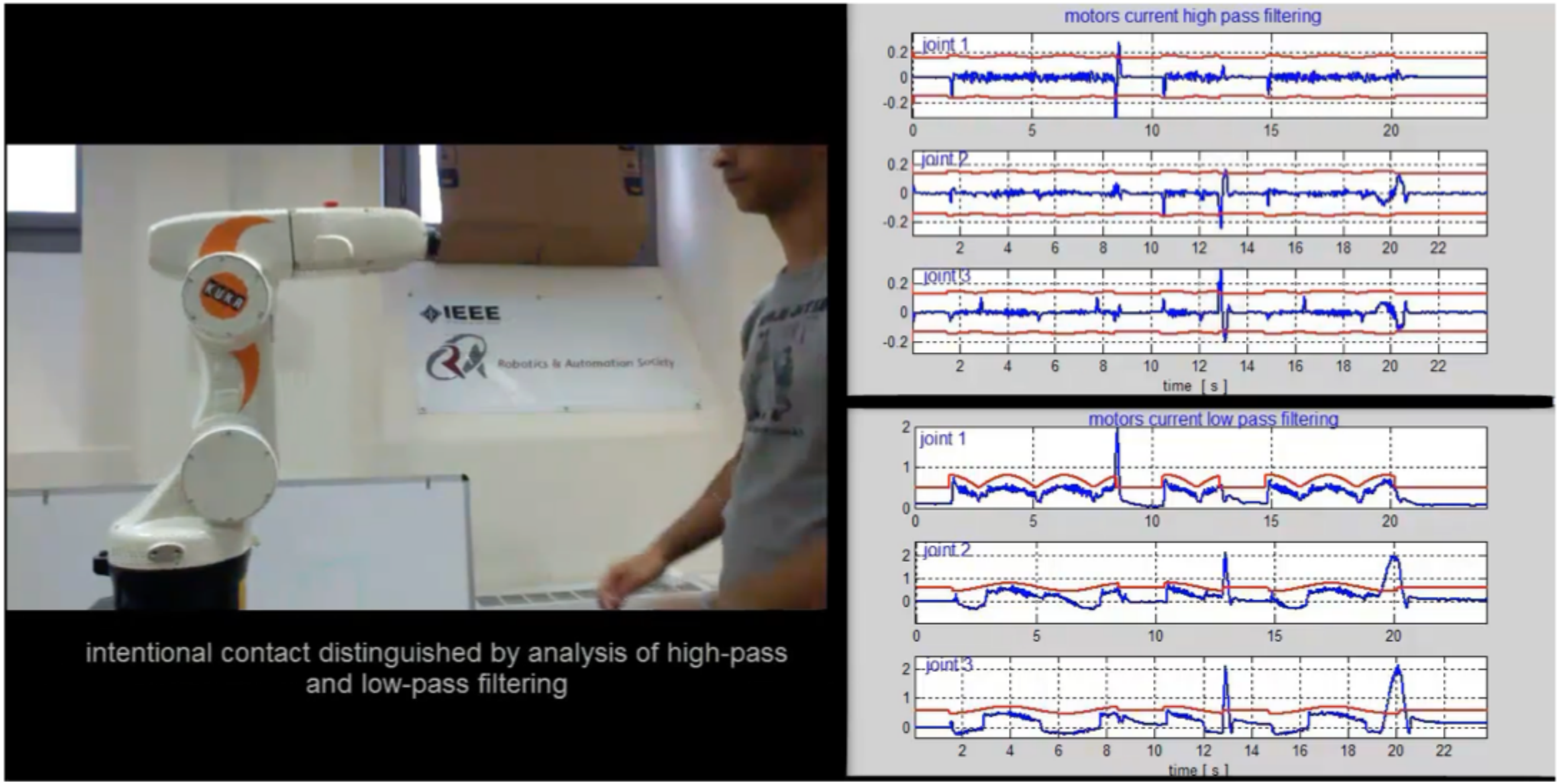
video



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

Distinguish accidental collisions from intentional contact and then collaborate

video



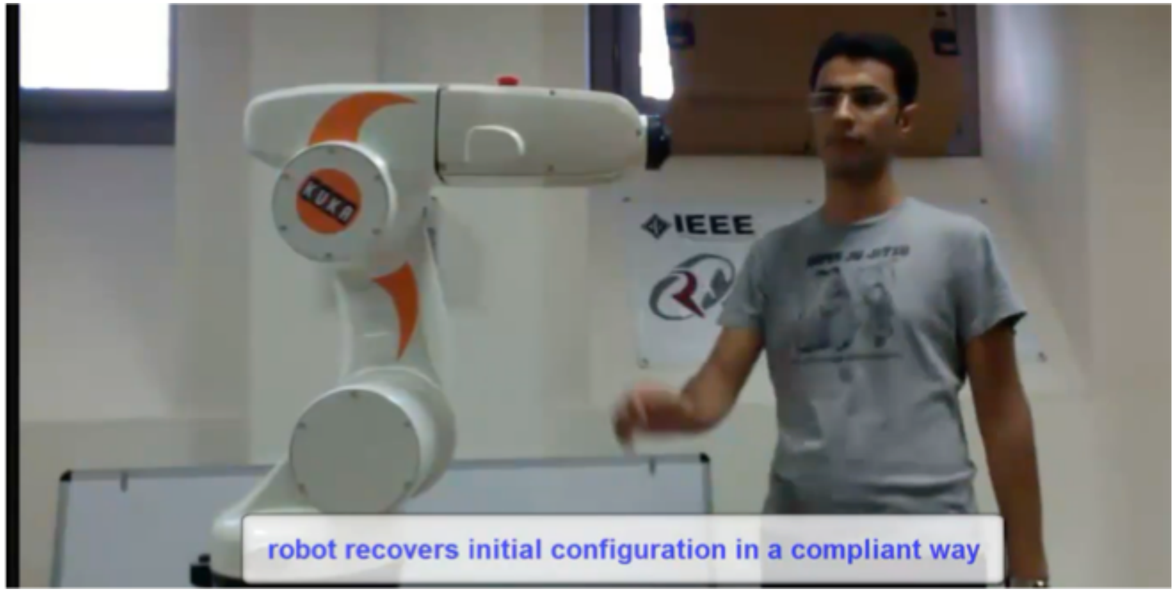
using both high-pass and low-pass filtering of motor currents
— here collaboration mode is manual guidance of the robot

Other possible robot reactions after collaboration mode is established

collaboration mode:
pushing/pulling
the robot

video

collaboration mode:
compliant-like
robot behavior



video

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