Elective in Robotics/Control Problems in Robotics

Physical Human-Robot Interaction

Collision Detection and Reaction

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Handling of robot collisions

- safety in physical Human-Robot Interaction (pHRI)
- robot dependability
  - 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
Safe and Autonomous Physical Human-Aware Robot Interaction

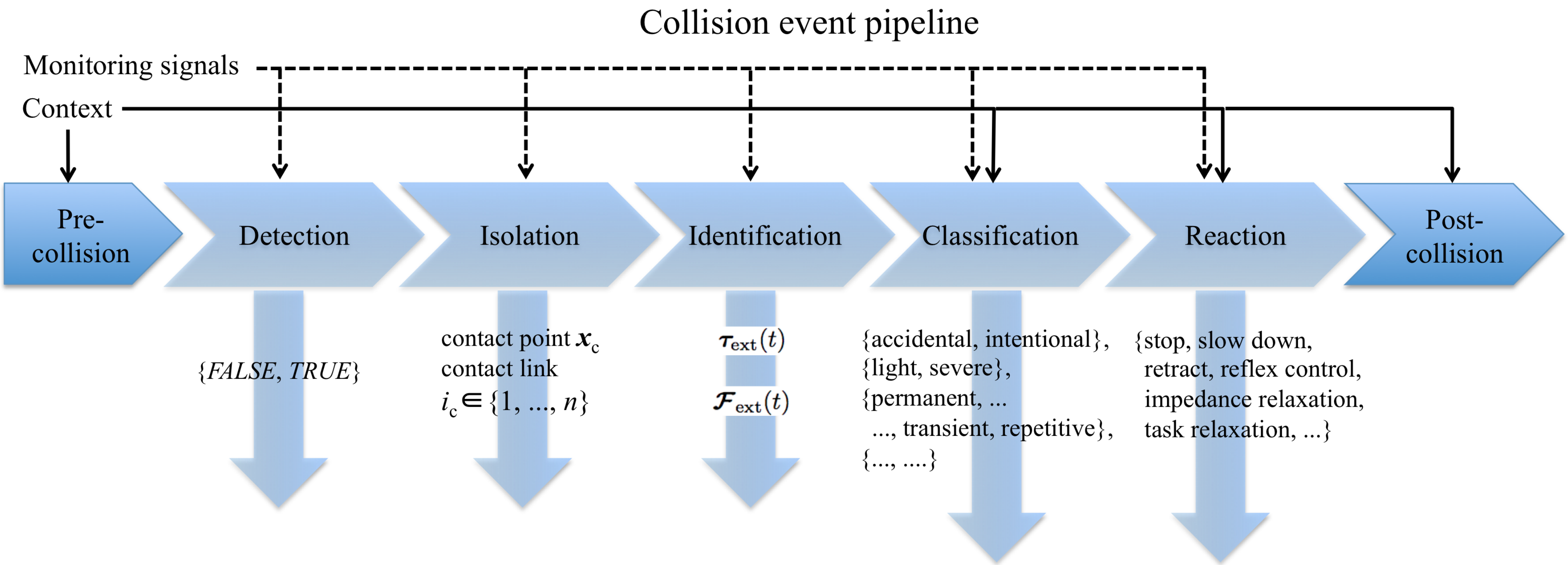
SAPHARI
FP7 IP
(2011-15)

SYMPLEXITY

SYMPLEXITY
H2020 IP (2015-18)

European projects that have funded our research developments

Collision event pipeline



Collision event pipeline

Monitoring signals

Context

Pre-collision

Detection

Isolation

Identification

Classification

Reaction

Post-collision

{*FALSE*, *TRUE*}

contact point $\boldsymbol{x}_c$
contact link
$i_c \in \{1, \ldots, n\}$

$\boldsymbol{\tau}_{\text{ext}}(t)$

$\boldsymbol{\mathcal{F}}_{\text{ext}}(t)$

{accidental, intentional},
{light, severe},
{permanent, ...
..., transient, repetitive},
{..., ...}

{stop, slow down,
retract, reflex control,
impedance relaxation,
task relaxation, ...}

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 ...)
- mainly intended for detection only, not for 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 torque on the 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 its 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 the 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 (heavy!)

video

  - the only feasible robot reaction is to stop!

Collisions as system faults

- robot model with (possible) collisions

control torque

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

inertia matrix

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

joint torque caused by link collision

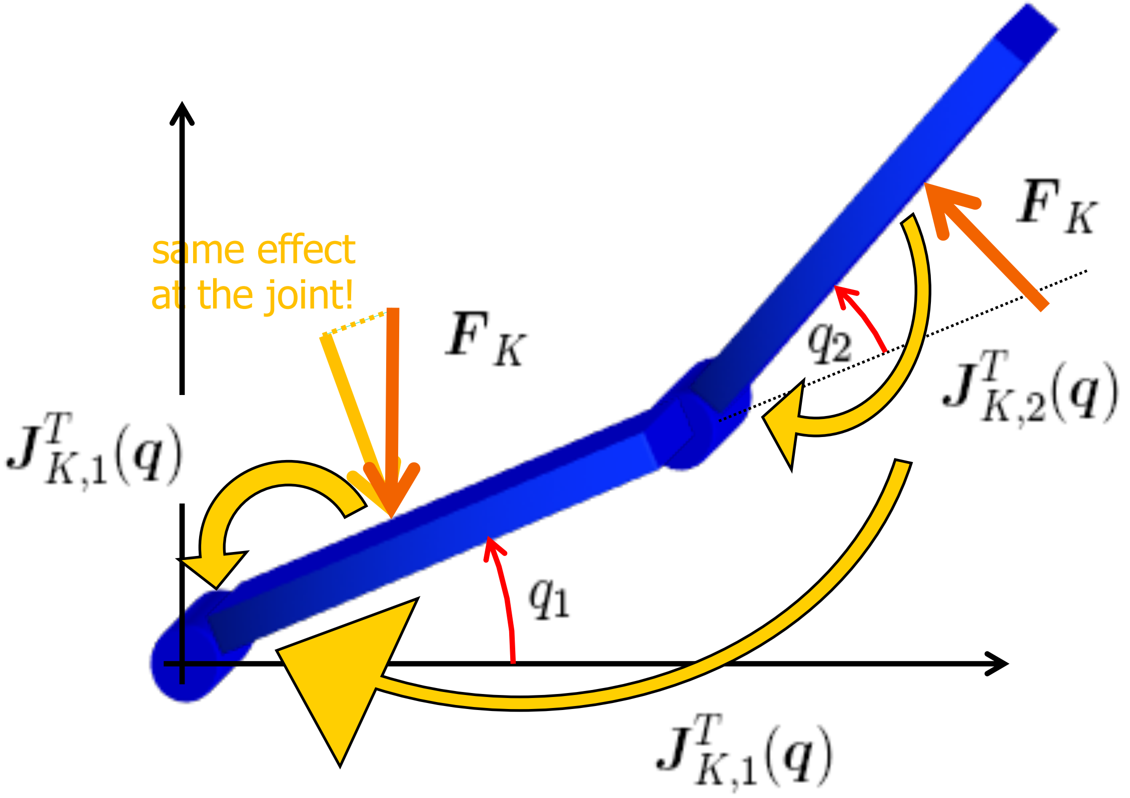
$$\boxed{\boldsymbol{\tau}_K=\boldsymbol{J}_K^T(\boldsymbol{q})\boldsymbol{F}_K}$$

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

- collisions may occur at any (unknown) location along the whole robot body, and with any (unknown) force
- simplifying assumptions (some may be relaxed)
  - manipulator is an open kinematic chain
  - single contact/collision
  - negligible friction (else, 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

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

- generalized momentum and its decoupled dynamics

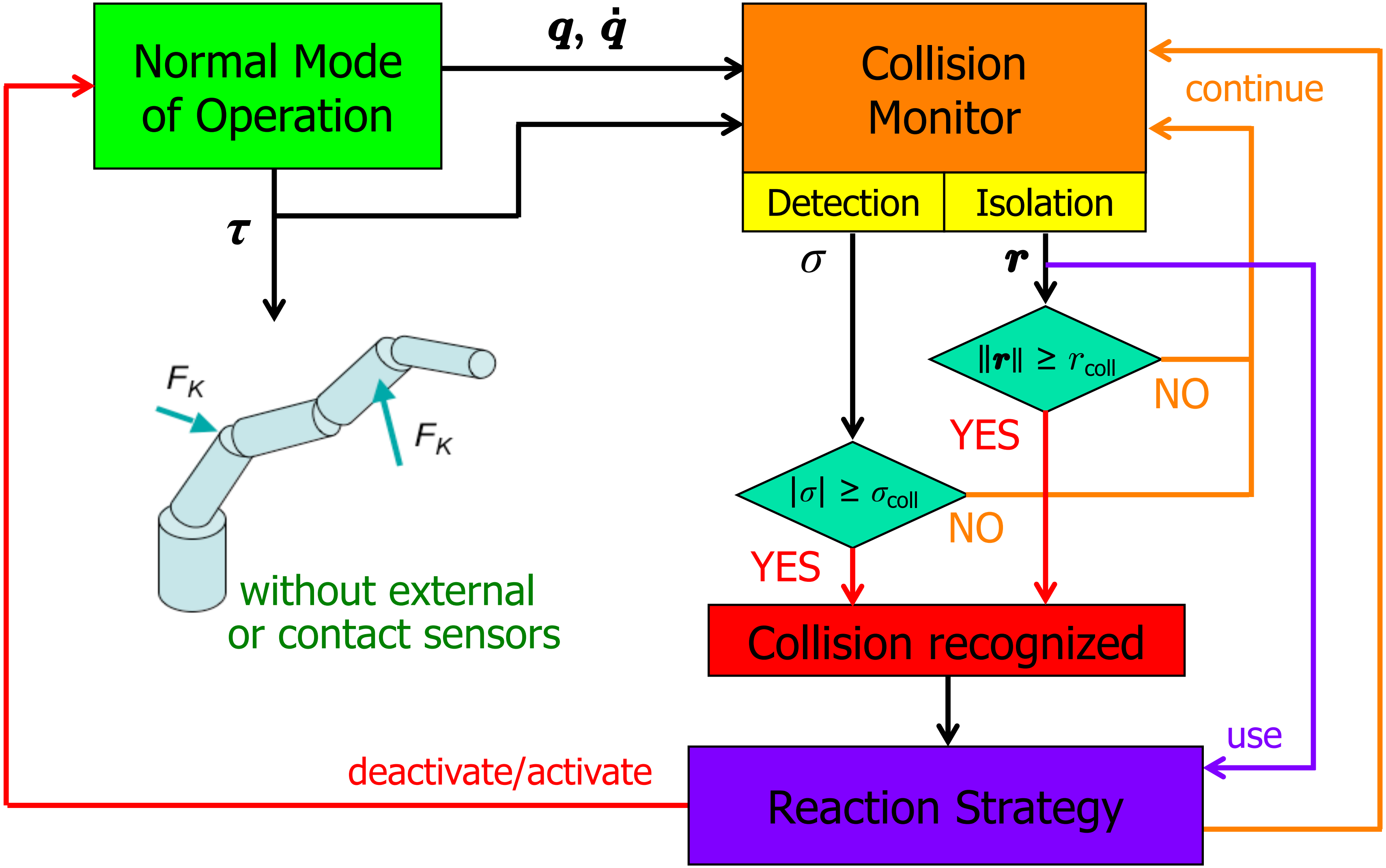
$$\boldsymbol{p} = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}}$$

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

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

prove this expression!

Monitoring collisions



Normal Mode of Operation

$\boldsymbol{q}, \dot{\boldsymbol{q}}$

Collision Monitor

Detection

Isolation

$\boldsymbol{\tau}$

σ

$\boldsymbol{r}$

continue

$\|\boldsymbol{r}\| \geq r_{\text{coll}}$

NO

YES

$|\sigma| \geq \sigma_{\text{coll}}$

NO

YES

without external
or contact sensors

Collision recognized

use

deactivate/activate

Reaction Strategy

Energy-based detection of collisions

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

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

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

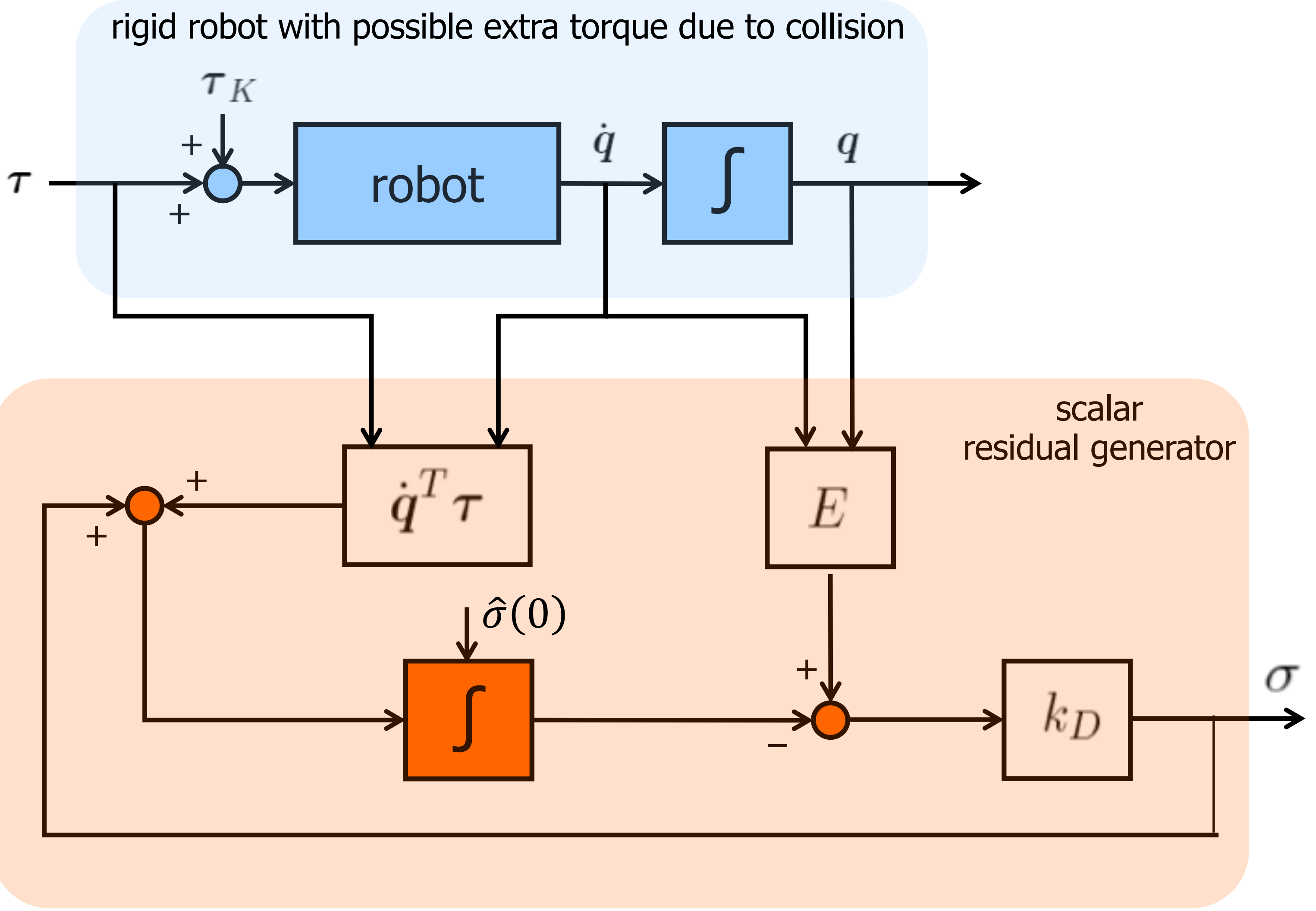
  - … and its dynamics (needed only for analysis)

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

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)

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

Analysis of the energy-based method

- a very simple scheme (scalar signal)

prove this!

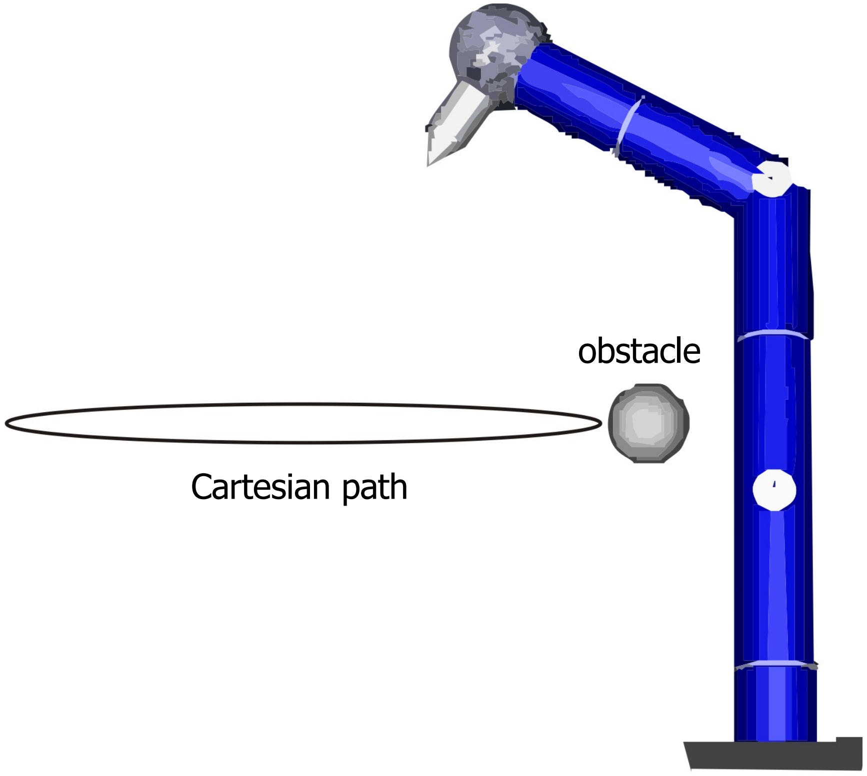
- rewritten as a monitor of the kinetic energy T, by replacing total energy E with T and adding $-\dot{q}^T g(q)$ in the integral
- it can only detect the presence of collision forces/torques (wrenches) that produce work on the linear/angular velocities (twists) at the contact
- moreover, it does not succeed when the robot stands still…

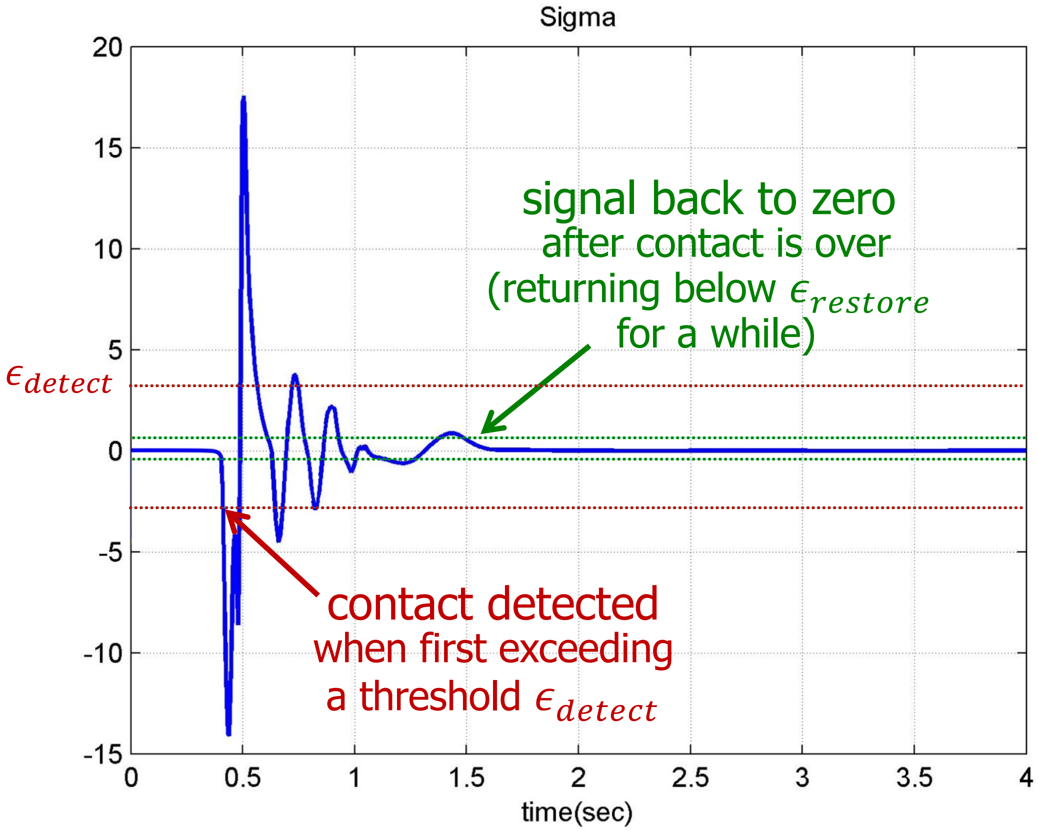
$$\dot{\boldsymbol{q}}^T \boldsymbol{\tau}_K = \dot{\boldsymbol{q}}^T \boldsymbol{J}_K^T(\boldsymbol{q}) \boldsymbol{F}_K = \boldsymbol{V}_K^T \boldsymbol{F}_K = 0 \iff \boxed{\boldsymbol{V}_K \perp \boldsymbol{F}_K}$$

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

Collision detection

simulation with a 7R robot





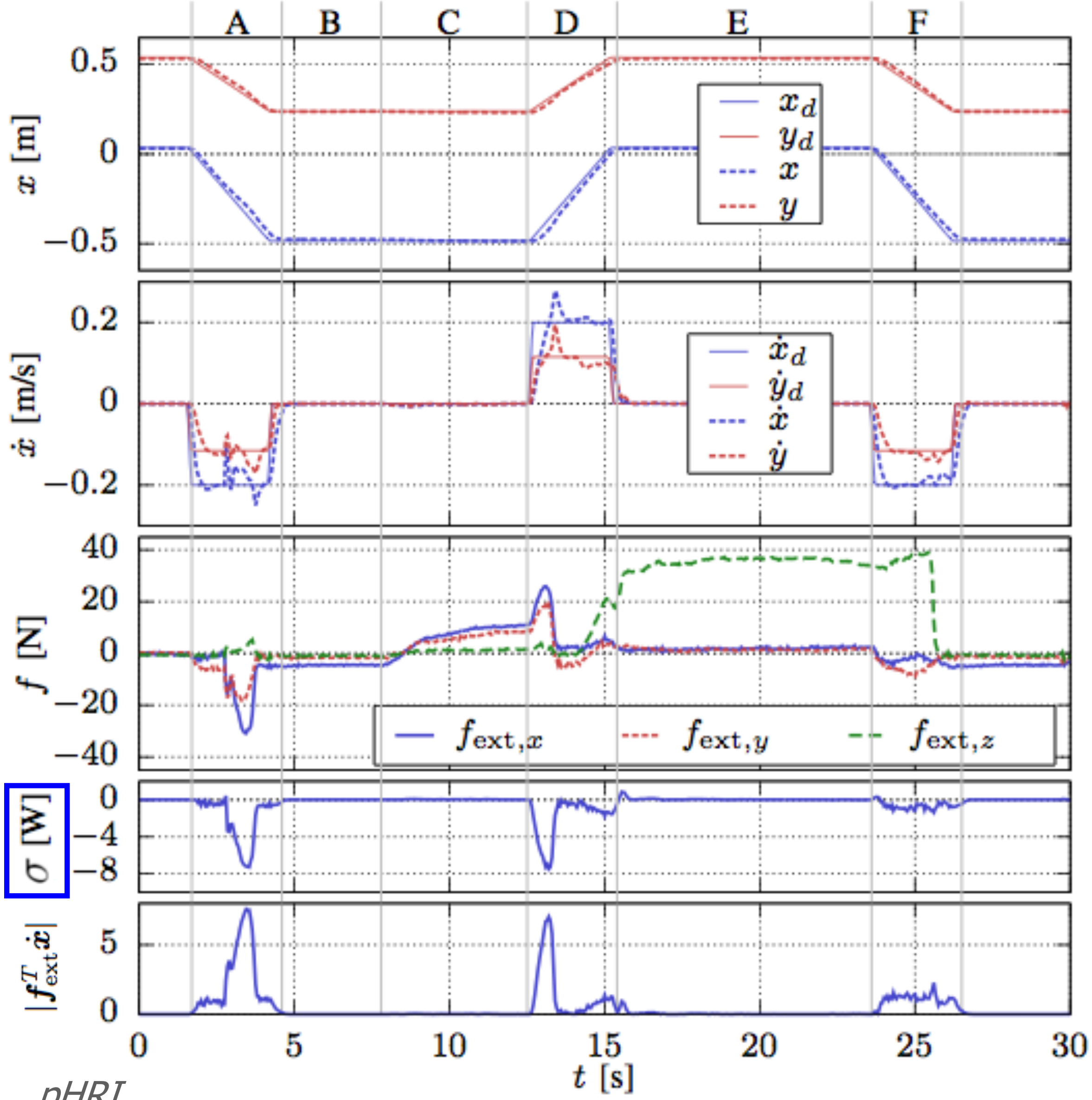
signal back to zero after contact is over (returning below $\epsilon_{restore}$ for a while)

contact detected when first exceeding a threshold ϵ_{detect}

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 or multiple 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

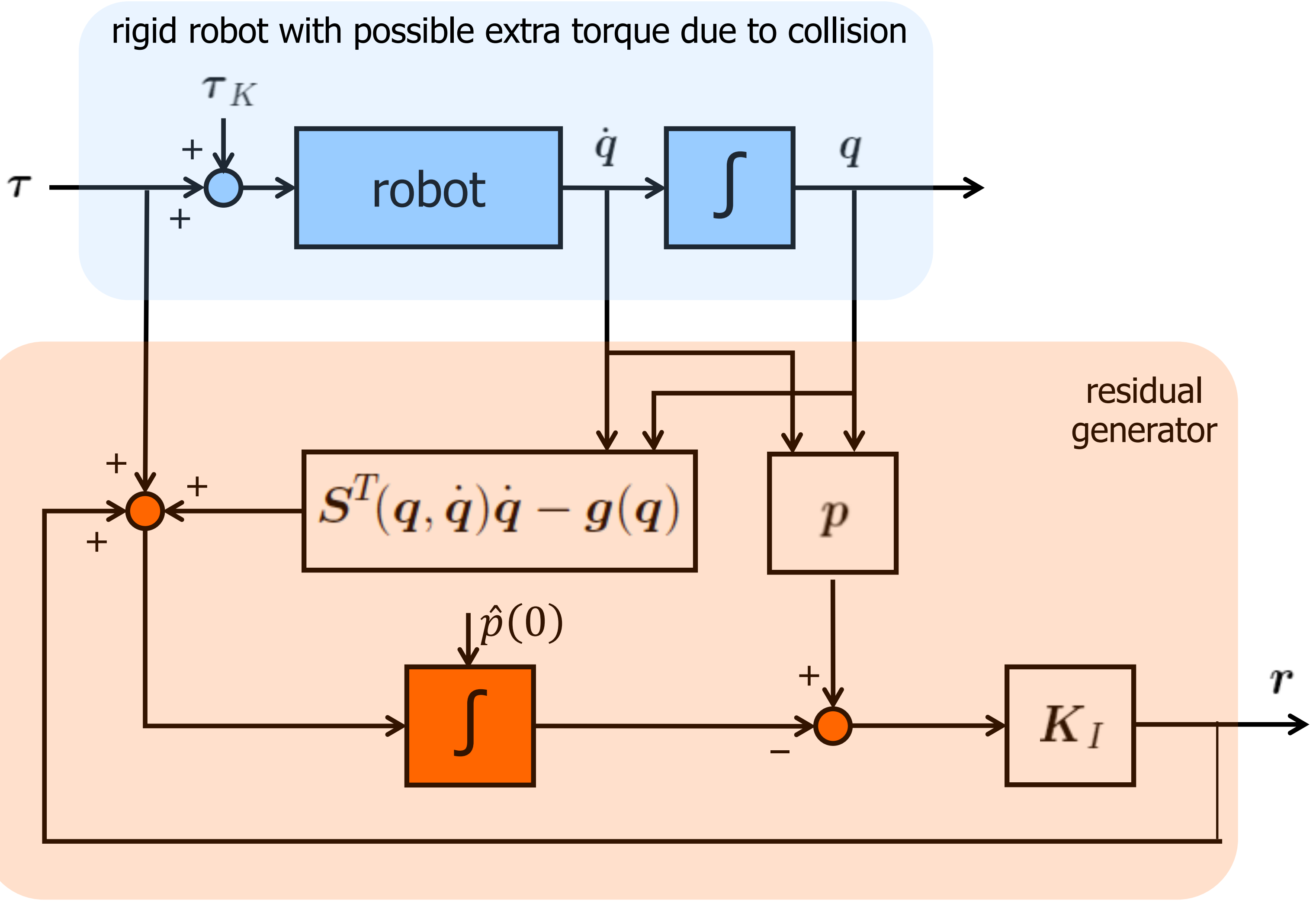
$$\dot{\boldsymbol{r}} = -\boldsymbol{K}_I \boldsymbol{r} + \boldsymbol{K}_I \boxed{\boldsymbol{\tau}_K} \qquad \frac{r_j(s)}{\tau_{K,j}(s)} = \frac{K_{I,j}}{s + K_{I,j}}$$

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

N 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



initialization
of integrators
$\hat{p}(0) = p(0)$
(zero if robot
starts at rest)

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

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

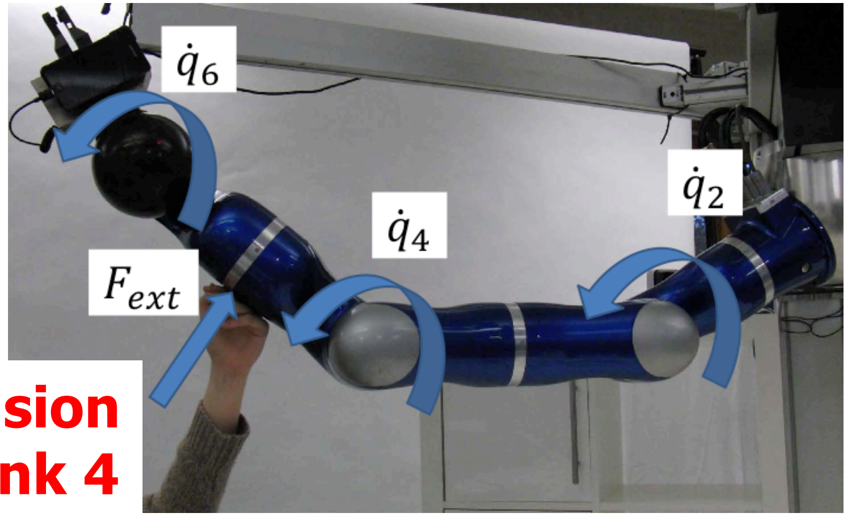
$$\boldsymbol{r} = \begin{bmatrix} * & \dots & * & * & \boxed{\begin{matrix} 0 & \quad\dots\quad & 0 \end{matrix}} \end{bmatrix}^T$$

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

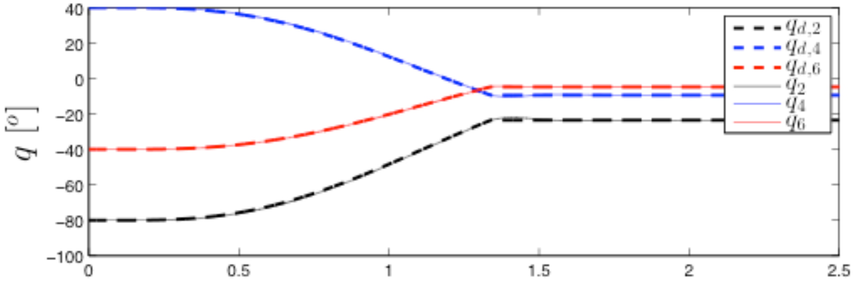
- residual vector contains directional information on the torque at the robot joints resulting from link collision (useful for robot reaction in post-impact phase)

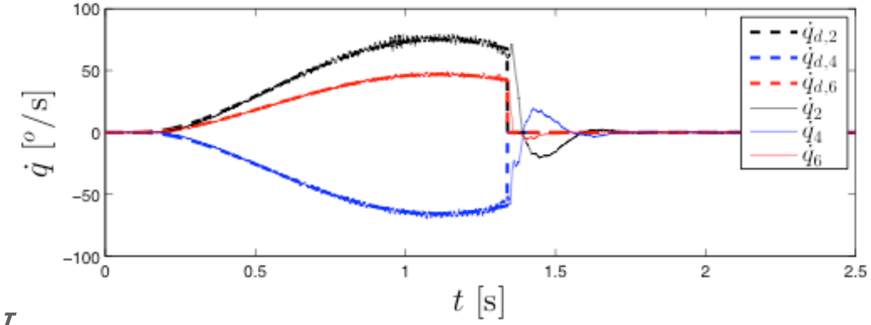
Momentum-based method

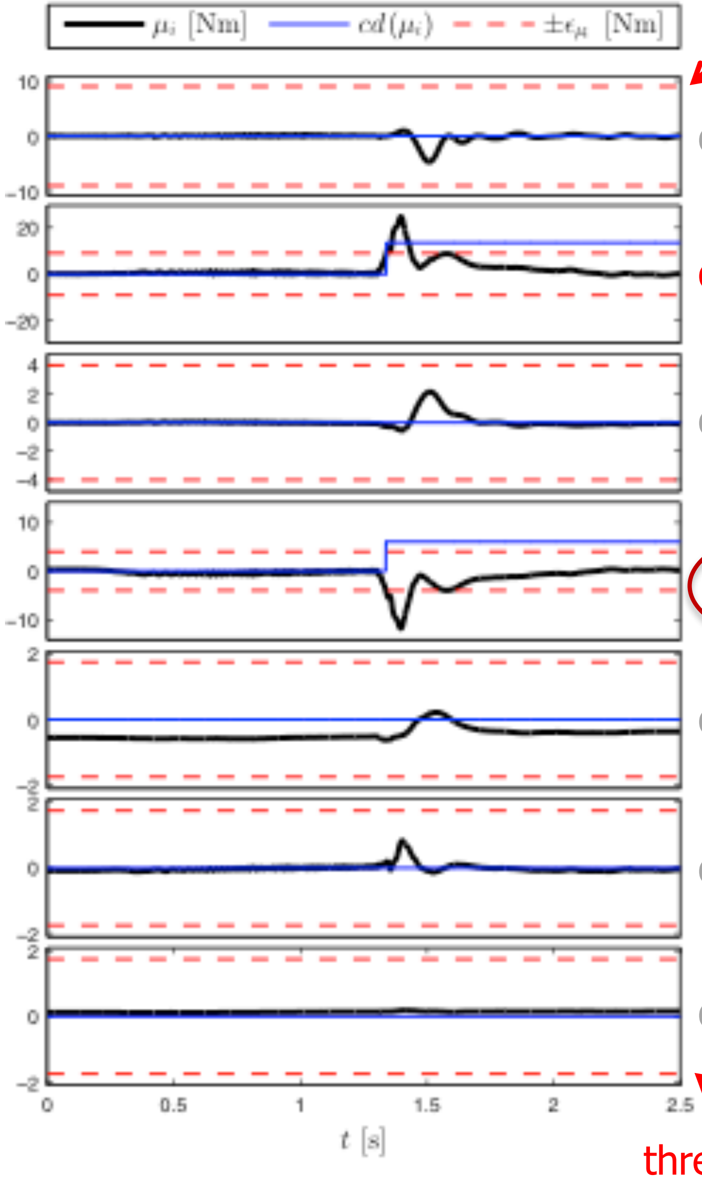
experiment on 3 moving links of a position controlled DLR LWR-III



collision at link 4







thresholds

cd$_1$ = off

cd$_2$ = ON

cd$_3$ = off

cd$_4$ = ON

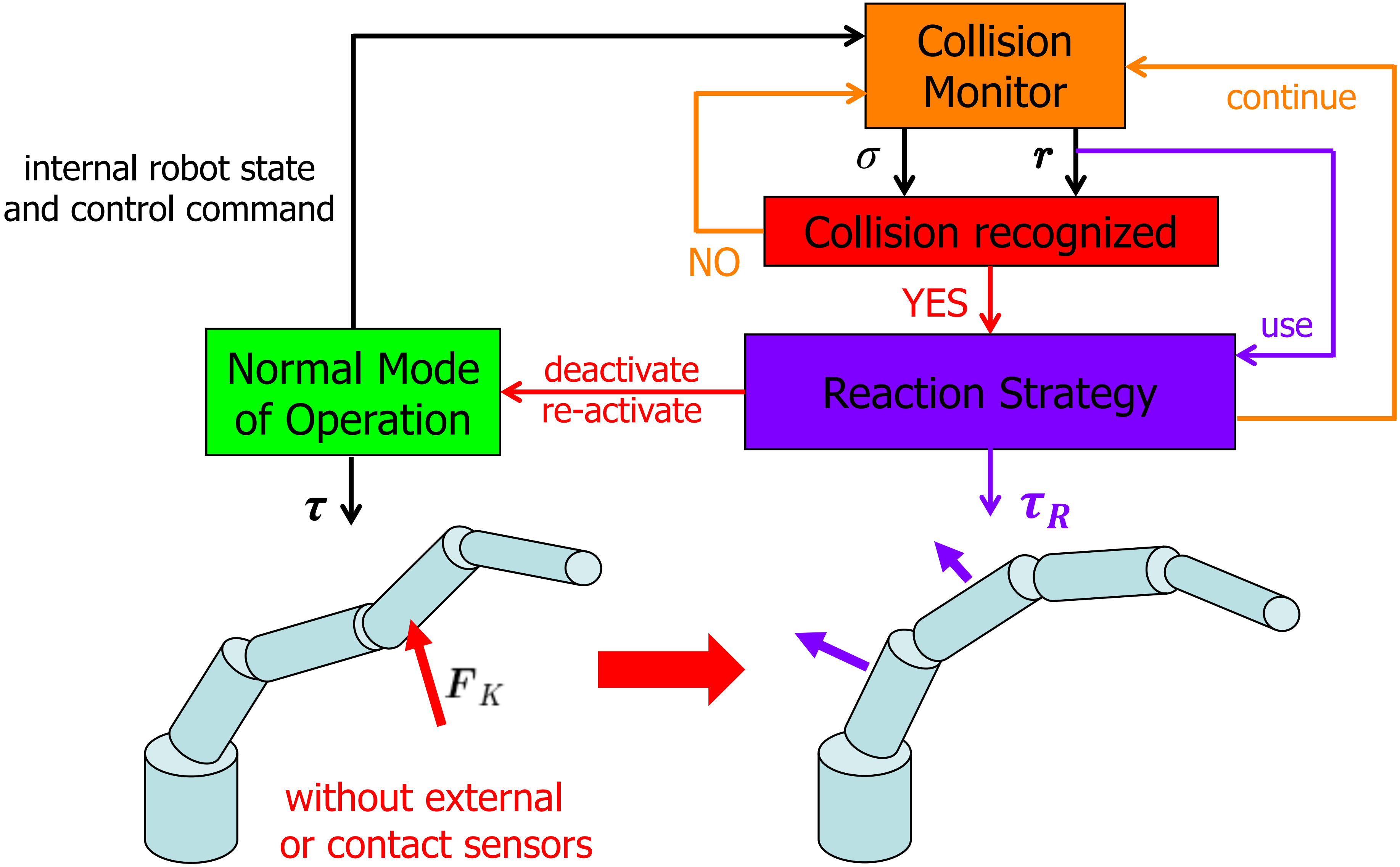
cd$_5$ = off

cd$_6$ = off

cd$_7$ = off

thresholds

Safe reaction to collisions



internal robot state
and control command

Collision Monitor

σ

$\boldsymbol{r}$

continue

NO

Collision recognized

YES

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

- "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

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

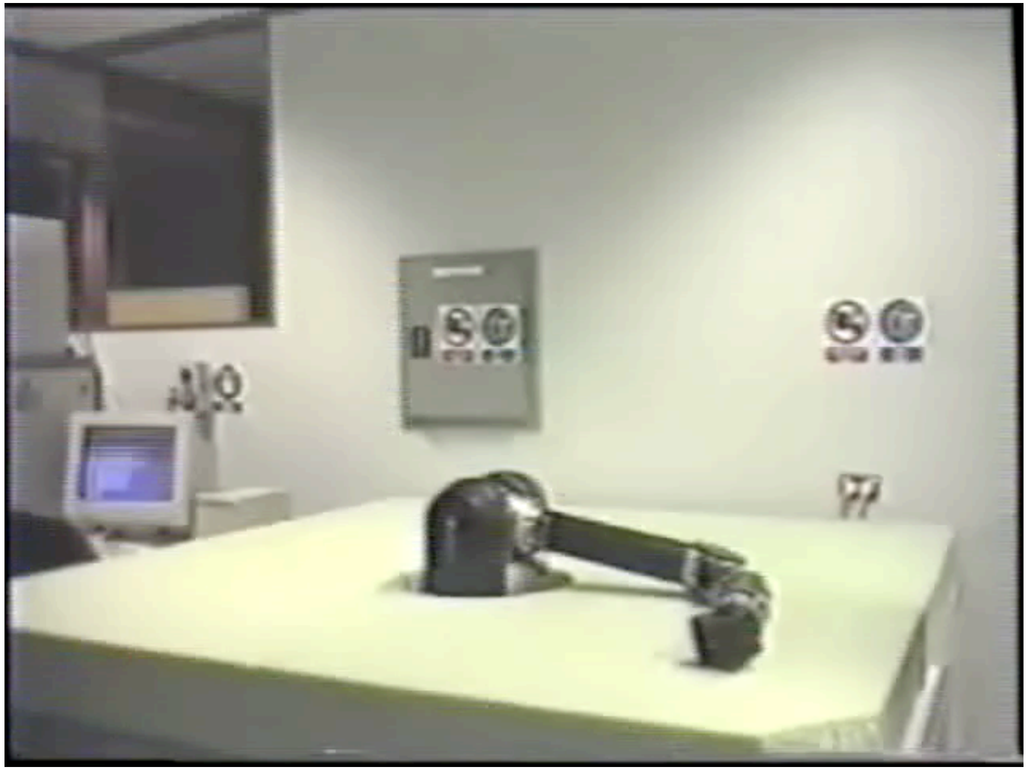
"joint torque command in same direction of collision torque"

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

Zero gravity operation

video
http://handbookofrobotics.org/view-chapter/69/videodetails/611

video



WAM Barrett

KUKA LWR4

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

$$\uparrow$$

here, only as result of human pushes ...

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

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

$$\boldsymbol{B}_m\ddot{\boldsymbol{\theta}} + \boldsymbol{\tau}_J = \boldsymbol{\tau}$$

friction at link side is negligible!

friction at motor side can be compensated!

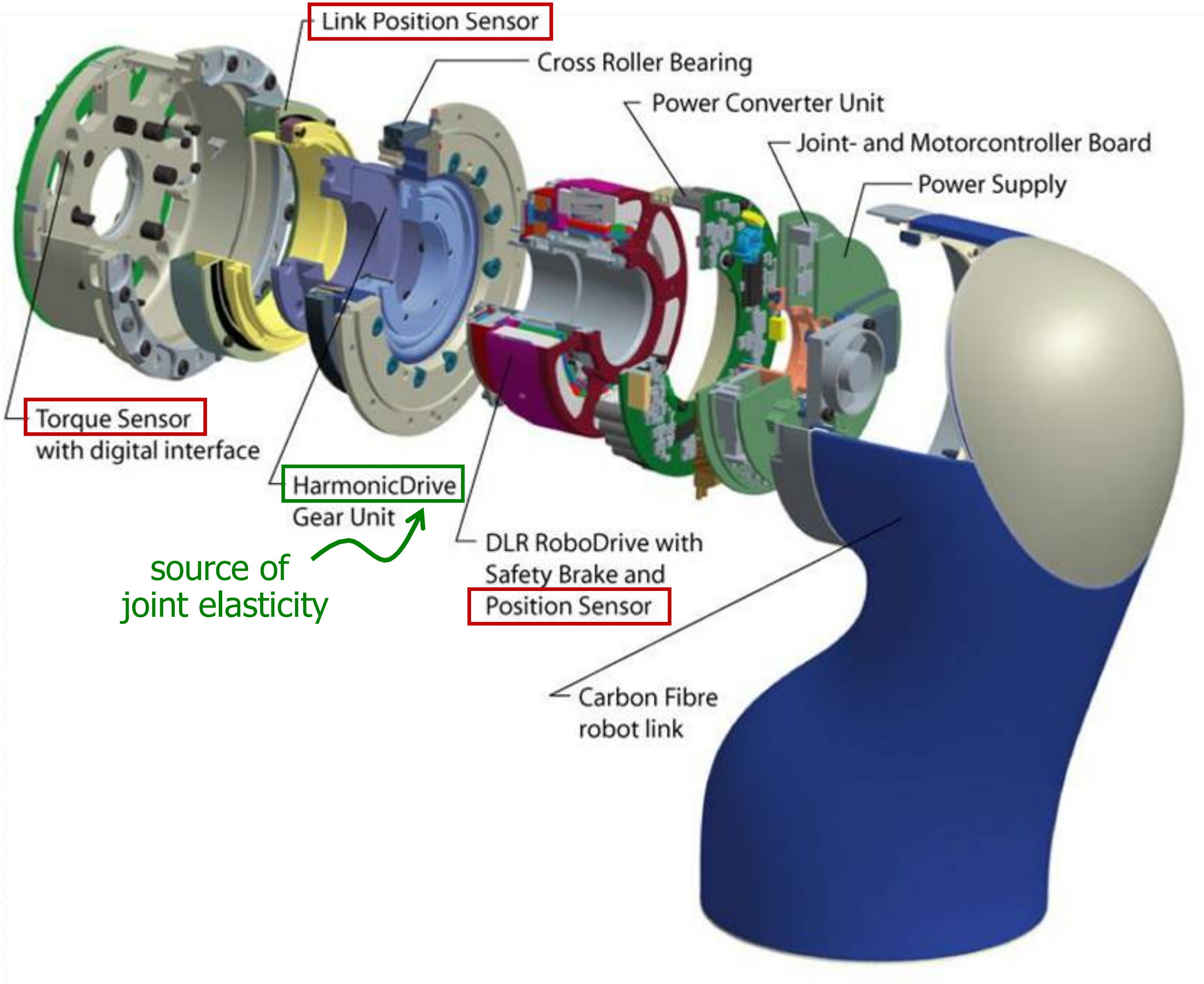
$$\boldsymbol{\tau}_J = \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q})$$

elastic torques at the joints

- proprioceptive sensing: motor positions and joint elastic torques

$$\boldsymbol{\theta} \quad \boldsymbol{\tau}_J \quad \Rightarrow \quad \boldsymbol{q} = \boldsymbol{\theta} - \boldsymbol{K}^{-1}\boldsymbol{\tau}_J$$

Exploded joint of LWR-III robot



source of
joint elasticity

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)

$$\tau = K_P(\underbrace{\theta_d - \theta}_{\text{motor position error}}) - K_D\dot{\theta} + K_{P\tau}(\underbrace{\tau_{J,d} - \tau_J}_{\text{elastic joint torque error}}) - K_{D\tau}\dot{\tau}_J + \underbrace{\tau_{J,d}}_{\text{elastic joint torque ffw command}}$$

- DLR "zero-gravity" condition is realized in a (quasi-static) approximate way, using just motor position measures

$$\bar{g}(\underbrace{\theta}_{\text{motor position}}) = g(\underbrace{q}_{\text{link position}}), \quad \forall(\theta, q) \in \Omega := \{(\theta, q) |\ \underbrace{K}_{\text{(diagonal) matrix of joint stiffness}}(\theta - q) = g(q)\}$$

Exact gravity cancellation
in robots with elastic joints

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{c}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}_q\dot{\boldsymbol{q}} + \boldsymbol{K}(\boldsymbol{q}-\boldsymbol{\theta}) = \boldsymbol{0}$$

$$\boldsymbol{B}\ddot{\boldsymbol{\theta}} + \boldsymbol{D}_\theta\dot{\boldsymbol{\theta}} + \boldsymbol{K}(\boldsymbol{\theta}-\boldsymbol{q}) = \boldsymbol{\tau}$$

impose the behavior of the
same robot without gravity

$$\boldsymbol{q}(t) \equiv \boldsymbol{q}_0(t) \quad \forall t \geq 0 \qquad\qquad \boldsymbol{\tau} = \boldsymbol{\tau}_g + \boldsymbol{\tau}_0$$

$$\Rightarrow \quad \boxed{\boldsymbol{\tau}_g = \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}_\theta\boldsymbol{K}^{-1}\dot{\boldsymbol{g}}(\boldsymbol{q}) + \boldsymbol{B}\boldsymbol{K}^{-1}\ddot{\boldsymbol{g}}(\boldsymbol{q})}$$

$$\dot{\boldsymbol{g}}(\boldsymbol{q}) = \frac{\partial \boldsymbol{g}(\boldsymbol{q})}{\partial \boldsymbol{q}}\,\dot{\boldsymbol{q}}$$

$$\ddot{\boldsymbol{g}}(\boldsymbol{q}) = \frac{\partial \boldsymbol{g}(\boldsymbol{q})}{\partial \boldsymbol{q}}\boldsymbol{M}^{-1}(\boldsymbol{q})\big(\boldsymbol{K}(\boldsymbol{\theta}-\boldsymbol{q}) - \boldsymbol{c}(\boldsymbol{q},\dot{\boldsymbol{q}}) - \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{D}_q\dot{\boldsymbol{q}}\big) + \sum_{i=1}^{n}\frac{\partial^2 \boldsymbol{g}(\boldsymbol{q})}{\partial \boldsymbol{q}\,\partial q_i}\,\dot{\boldsymbol{q}}\,\dot{q}_i$$

it requires full state feedback

A. De Luca, F. Flacco, *IEEE CDC 2010*

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 r_{EJ} 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

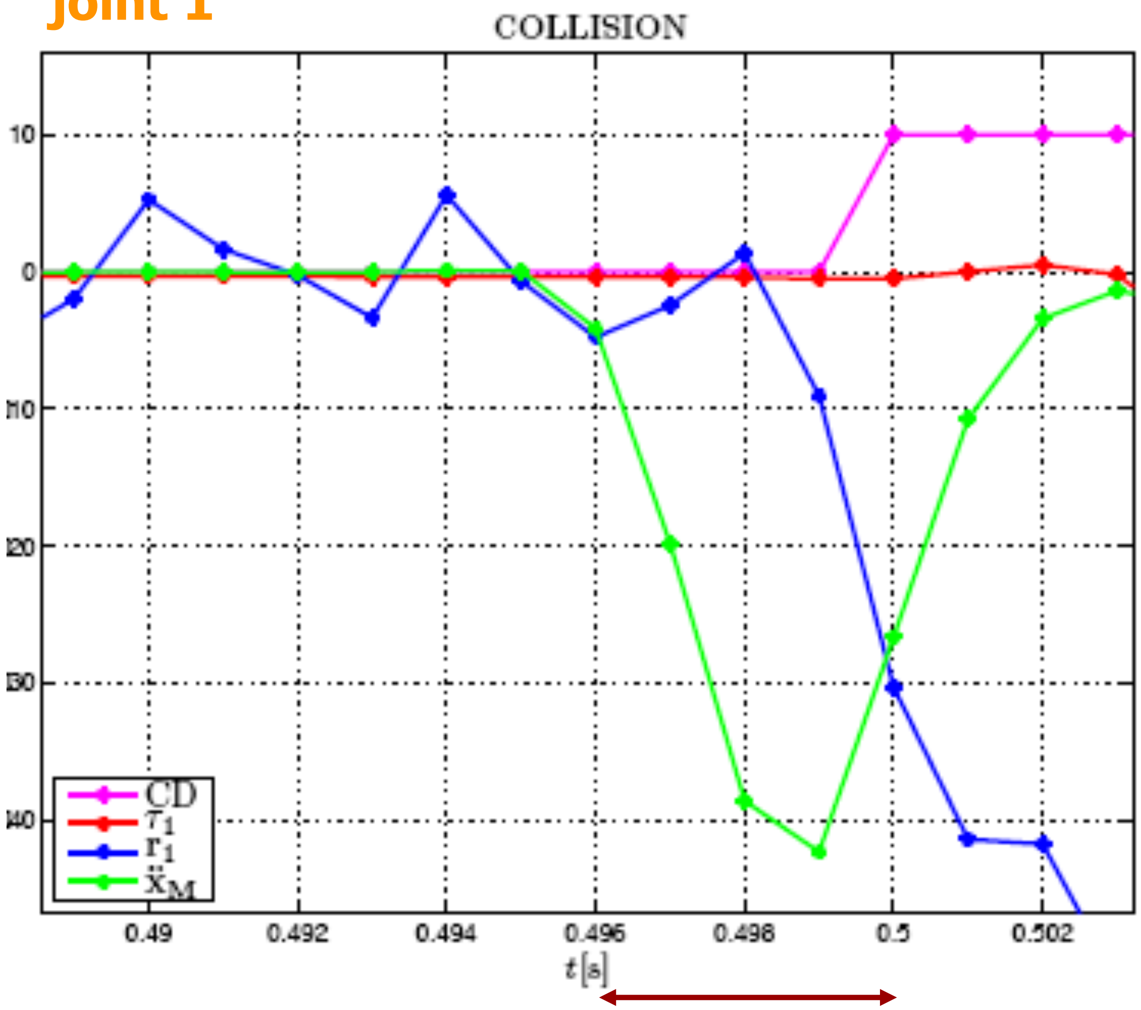
planned trajectory ends just after
the position of the dummy head

strategy 2: floating reaction

impact velocity is rather low here and
the robot stops switching to float mode

Delay in collision detection

joint 1



2-4 msec!

impact with
the dummy head

🟥 measured (elastic) joint torque

🟦 residual r_1

🟪 0/1 index for detection

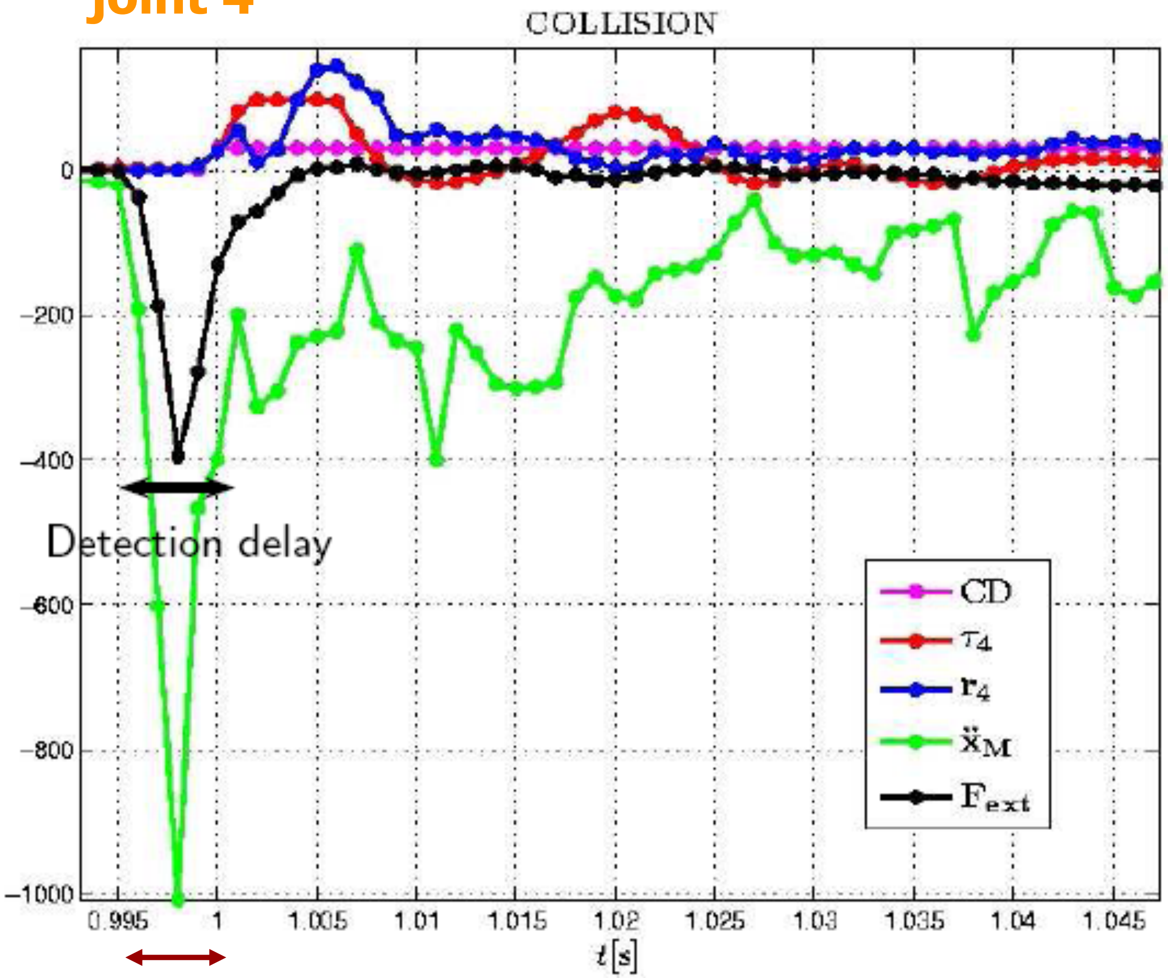
🟩 dummy head acceleration

gain K_I = diag{25}

threshold = 5-10% of max rated torque

Delay in collision detection

joint 4



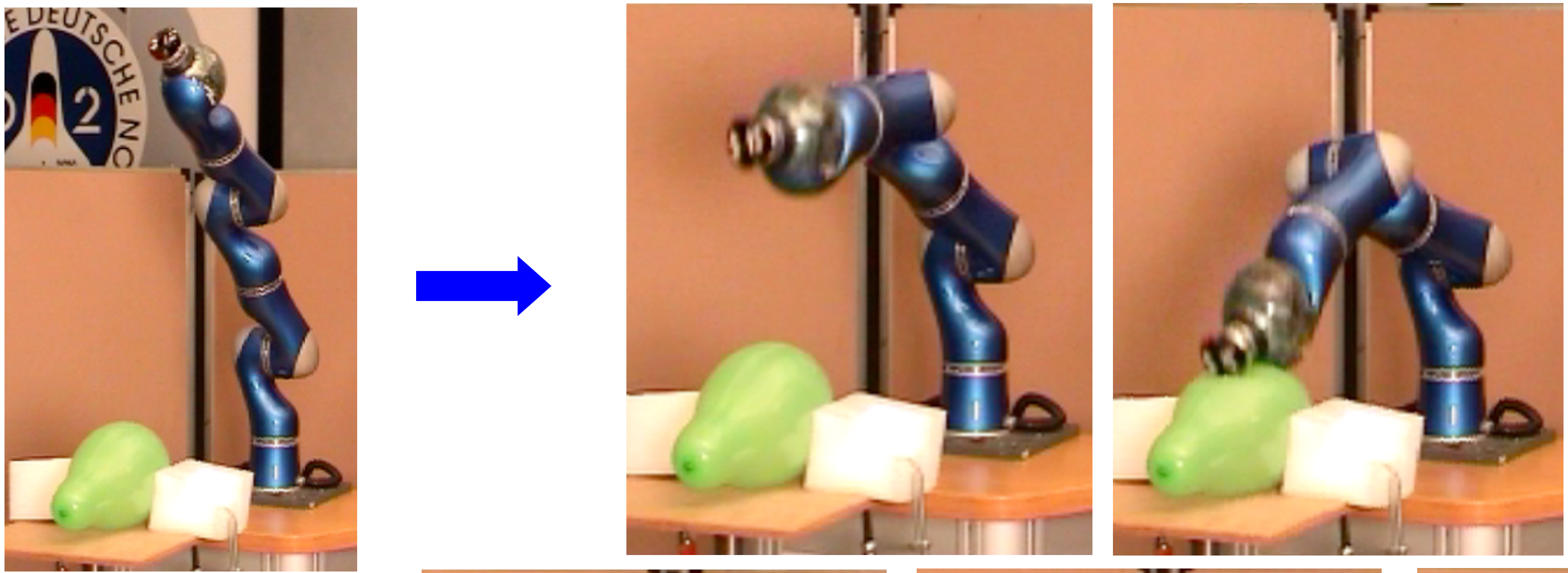
5 msec

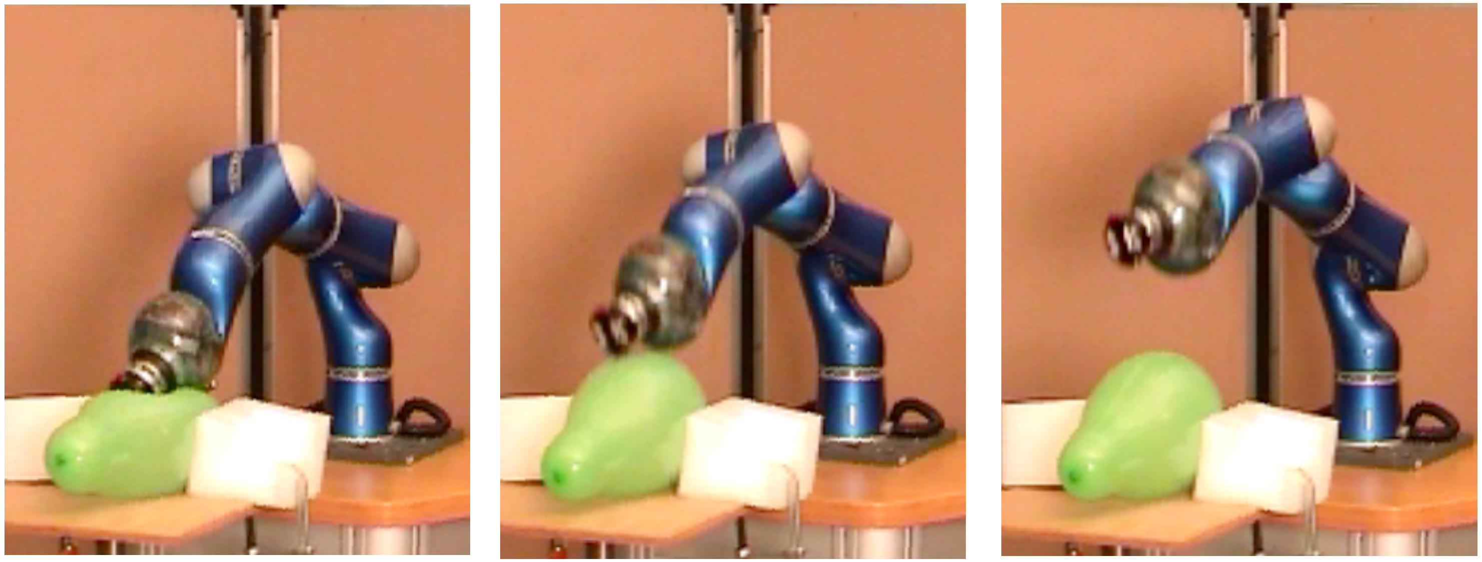
impact with
the dummy head
+ F/T sensing

- 🟥 measured (elastic) joint torque
- 🟦 residual r_4
- ⬛ sensed external force
- 🟪 0/1 index for detection
- 🟩 dummy head acceleration

Experiments with LWR-III robot

balloon impact





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

Balloon impact

video

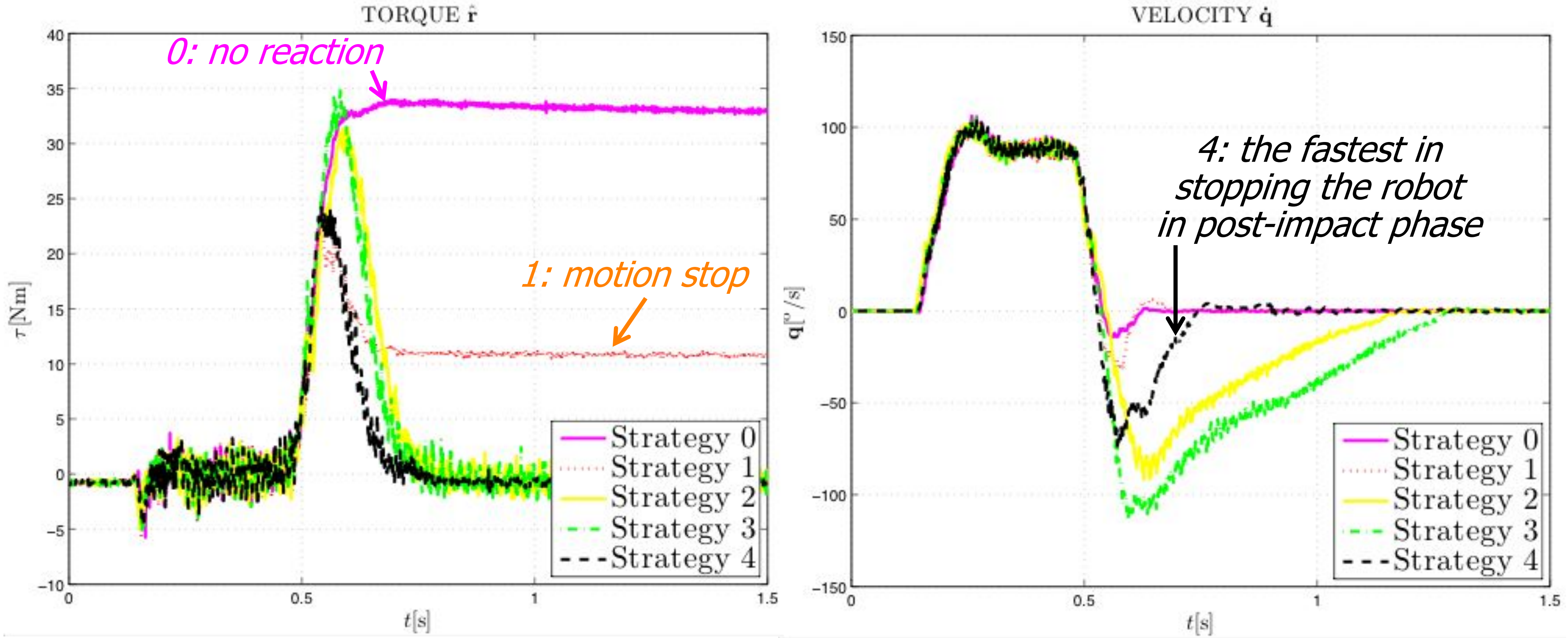
coordinated
joint motion
@90^o/sec

strategy 4: admittance mode reaction

Experimental comparison of strategies

balloon impact

- residual and velocity at joint 4 with various reaction strategies



0: no reaction

1: motion stop

4: the fastest in stopping the robot in post-impact phase

impact at 90^{o}/sec with coordinated joint motion

Human-Robot Interaction

- first impact @60°/sec

video

strategy 4: admittance mode

video

strategy 3: reflex torque

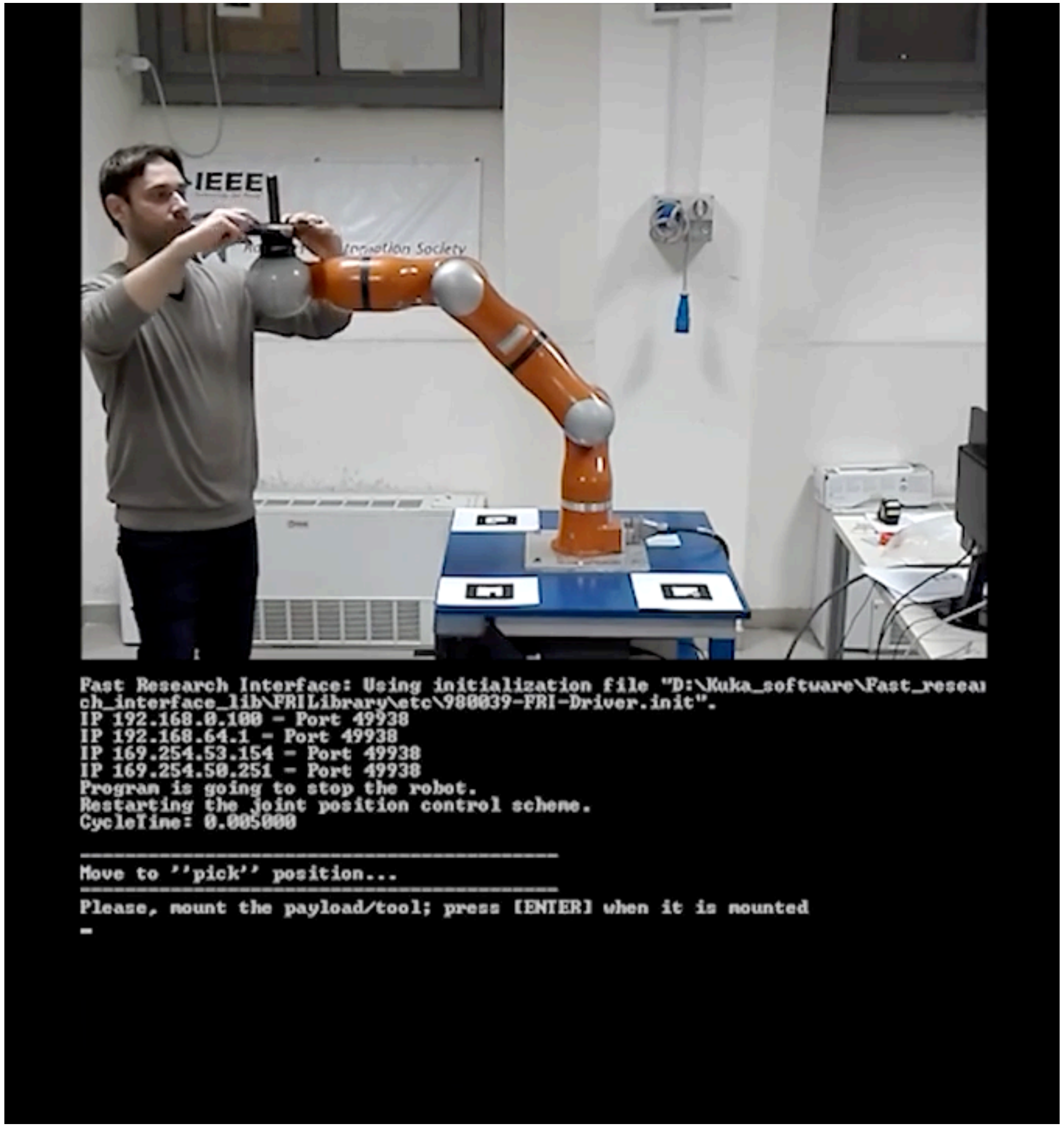
Human-Robot Interaction

- first impact @90°/sec

video

strategy 3: reflex torque

Need for a good dynamic model ...



```
Fast Research Interface: Using initialization file "D:\Kuka_software\Fast_resea
ch_interface_lib\FRILibrary\etc\980039-FRI-Driver.init".
IP 192.168.0.100 - Port 49938
IP 192.168.64.1 - Port 49938
IP 169.254.53.154 - Port 49938
IP 169.254.50.251 - Port 49938
Program is going to stop the robot.
Restarting the joint position control scheme.
CycleTime: 0.005000

----------------------------------------
Move to ''pick'' position...
----------------------------------------
Please, mount the payload/tool; press [ENTER] when it is mounted
_
```

- performance of model-based detection/isolation methods is limited by uncertainties and unmodeled dynamics (e.g., when adding an unknown payload)
- there is a need for accurate (and fast) online schemes for identification
- here, ~10 small motions are sufficient to capture the mass and CoM of a payload (becoming part of dynamic parameters of the last link)

video @IROS17
https://youtu.be/fNP6smdp7aE

Simultaneous use of two residuals

- use of the two types of introduced residuals, with different thresholds
  - momentum-based vector $\boldsymbol{r}$ + energy-based scalar σ (less sensitive at slow speed)
  - more robust to dynamic uncertainties (in particular, to unmodeled friction)

LARA 5
6R cobot
by Neura
Robotics

video
@ICRA23

Other uses of residuals

- the design concept of a residual can be used also to estimate online any “missing” dynamic term in the model of a (mechanical) system
  - it has in fact the structure of a “disturbance” or “input” observer
- we have used it to estimate (and control) at run time the time-varying nonlinear stiffness of a VSA device (which cannot be directly measured …)
- being a (first-order) filtered version of the unknown/missing term, it may be used as a compensation signal within any control law, without having “algebraic loops” or attempting a (difficult) model-based identification
- consider a (relevant) motor-side friction τ_F in a robot with elastic joints

$$B\ddot{\theta} + K(\theta - q) = B\ddot{\theta} + \tau_J = \tau + \tau_F$$

$$\boxed{r_F = K_F\left[B\dot{\theta} - \int_0^t \left(\tau - \tau_J + r_F\right) ds\right]}$$

$$\Rightarrow \dot{r}_F = K_F\left[\tau_F - r_F\right]$$

$$\Rightarrow r_{F,i}(s) = \frac{\tau_{F,i}(s)}{1 + \left(1/k_{F,i}\right)s}$$

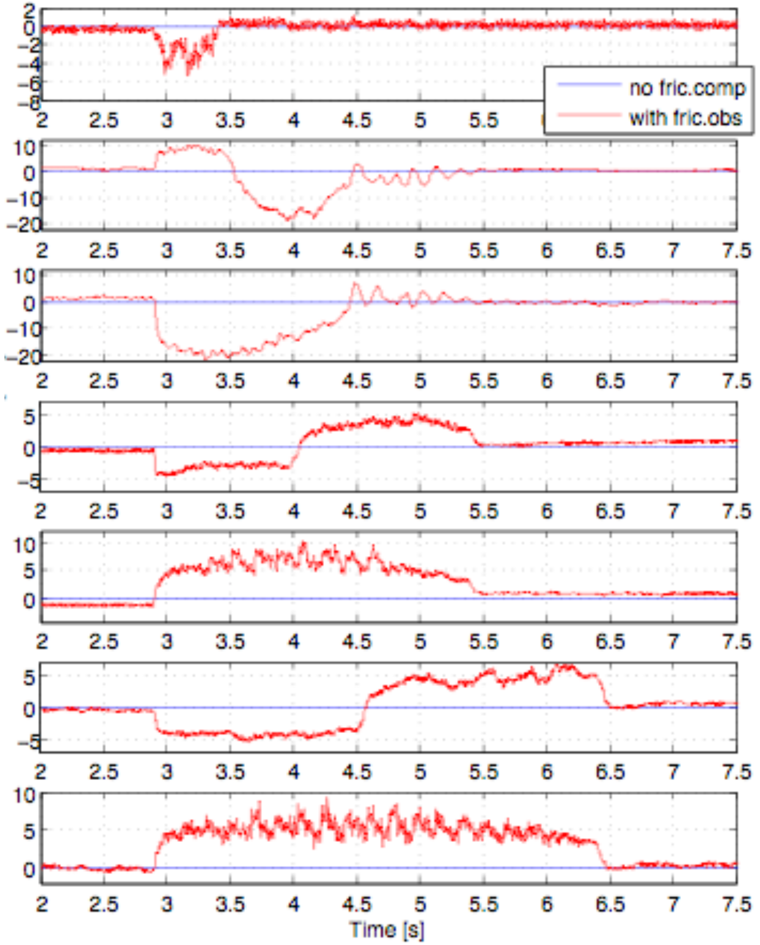
⇒ model-less friction compensation: $\tau = \tau_{anycontrol} - r_F$

Experiments on friction compensation

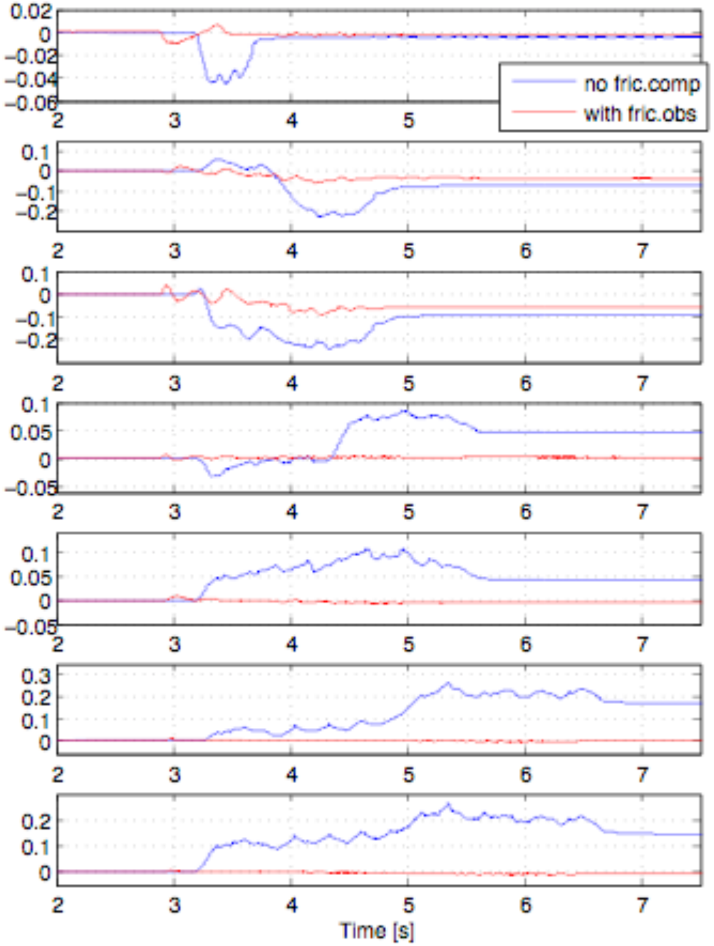
- results on the DLR 7R MIRO medical robot

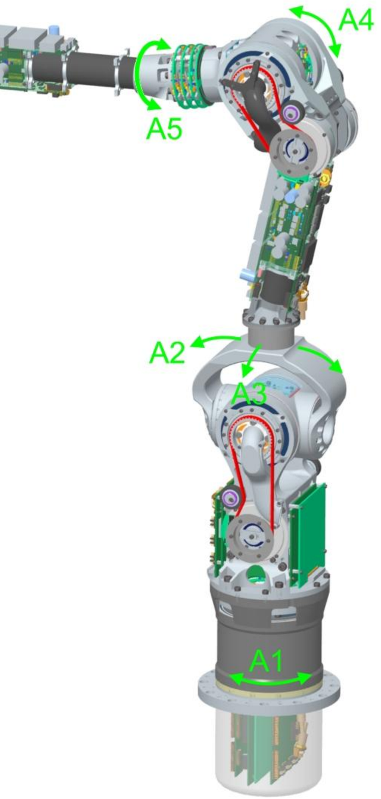
used then on-line
in a control law...

friction estimate via residuals



position error

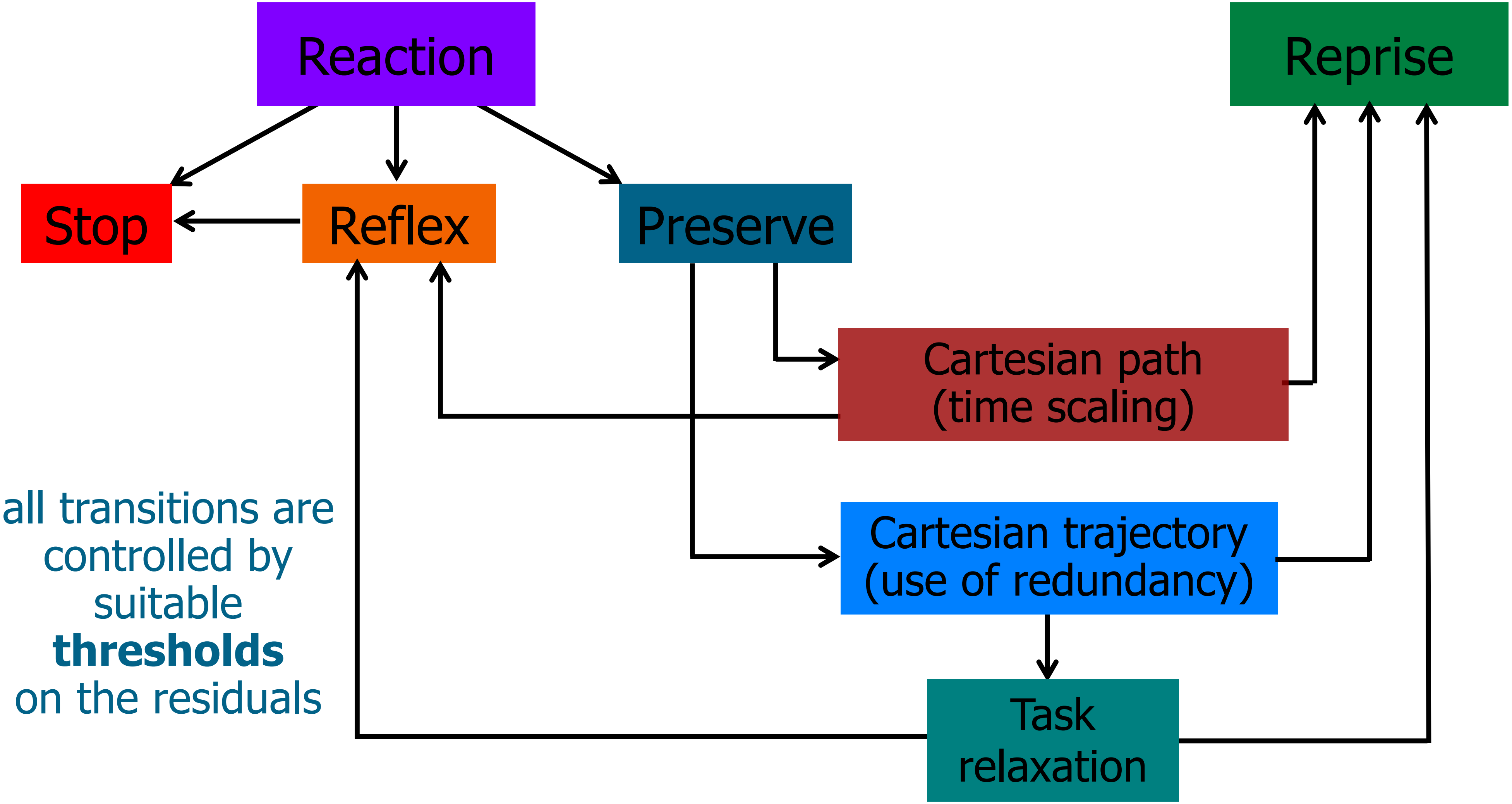




HD at the joints
⇒ elastic joint dynamic model

“Portfolio” of reaction strategies

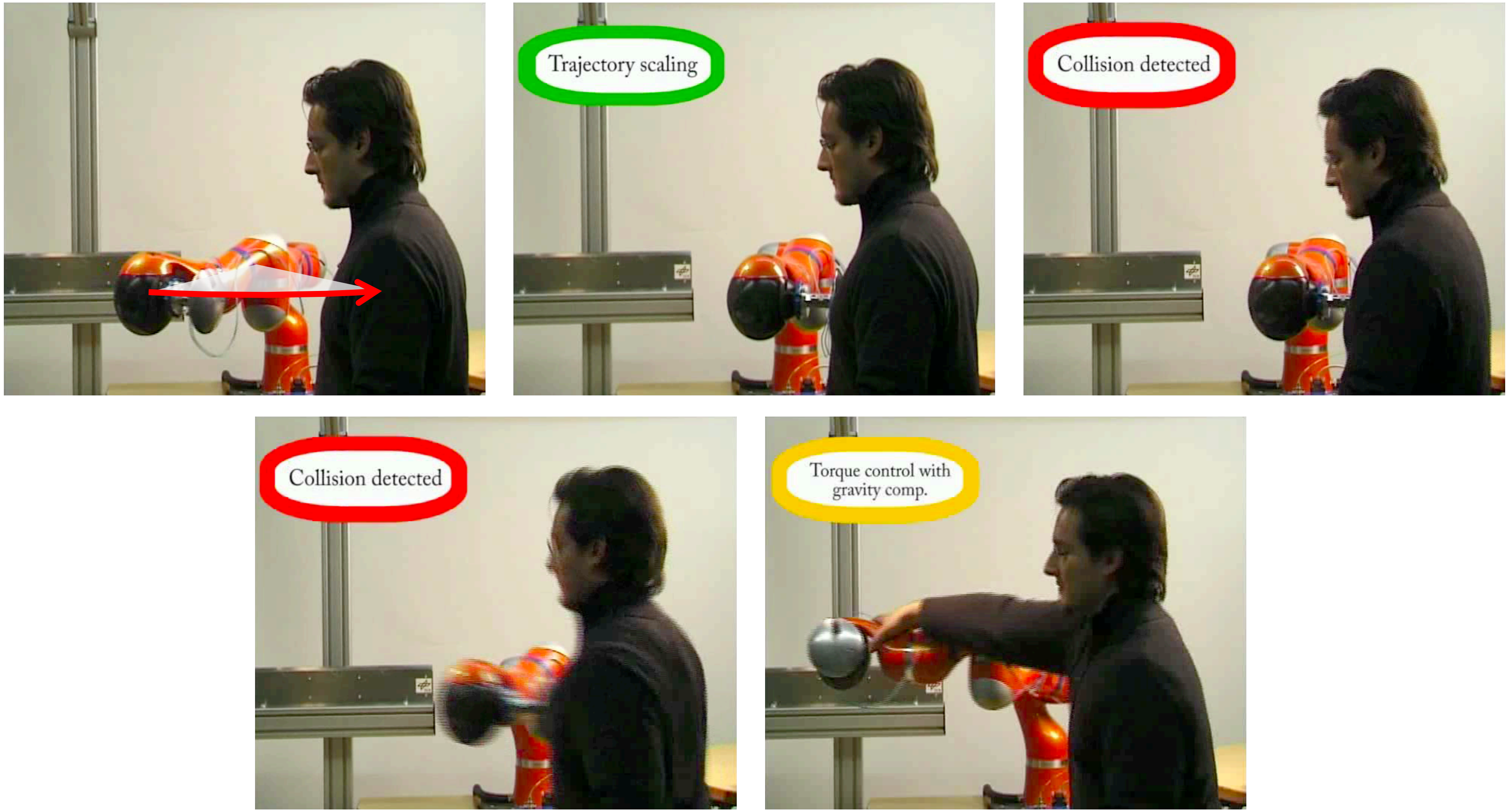
residual amplitude ∝ severity level of collision



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

Experiments with LWR-III robot

time scaling



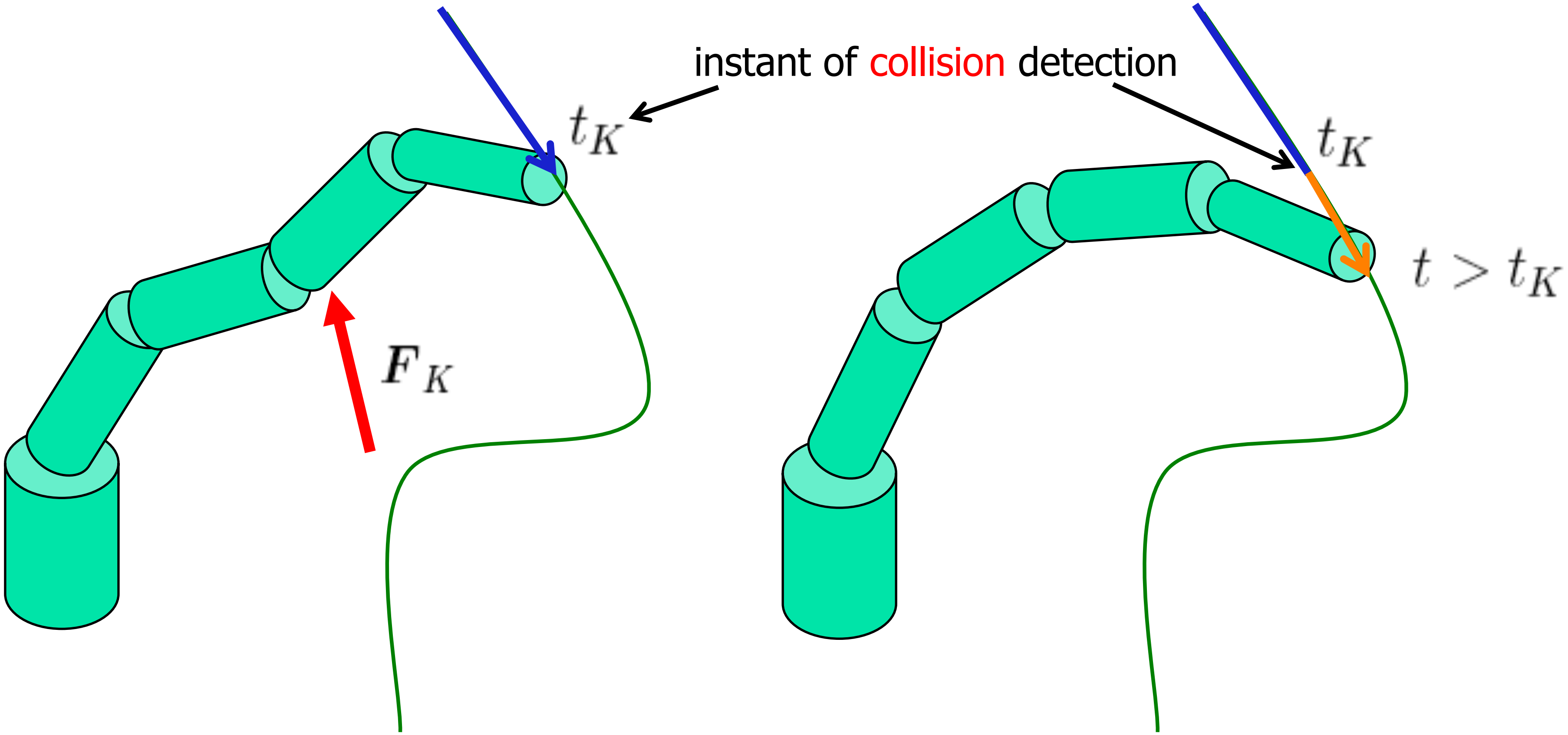
- robot is position-controlled (on a given geometric path)
- timing law slows down, stops, possibly reverses (and then reprises)

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) the execution of the planned Cartesian trajectory for the end-effector



instant of collision detection

Task kinematics

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

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

- (all) generalized inverses of the task Jacobian

$$\boldsymbol{J}(\boldsymbol{q})\boldsymbol{G}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q}) = \boldsymbol{J}(\boldsymbol{q}), \qquad \forall \boldsymbol{q}$$

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

$$\ddot{\boldsymbol{q}} = \boldsymbol{G}(\boldsymbol{q})\left(\boxed{\ddot{\boldsymbol{x}}} - \dot{\boldsymbol{J}}(\boldsymbol{q})\dot{\boldsymbol{q}}\right) + \left(\boldsymbol{I} - \boldsymbol{G}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})\right)\underset{\uparrow}{\boxed{\ddot{\boldsymbol{q}}_0}}$$

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

$$\begin{aligned}\boldsymbol{\tau} &= \boldsymbol{M}(\boldsymbol{q})\boldsymbol{G}(\boldsymbol{q})\left[\overset{\ddot{\boldsymbol{x}}_d + \boldsymbol{K}_P\boldsymbol{e} + \boldsymbol{K}_D\dot{\boldsymbol{e}}}{\overset{\downarrow}{\boxed{\ddot{\boldsymbol{x}}}}} - \dot{\boldsymbol{J}}(\boldsymbol{q})\dot{\boldsymbol{q}} + \boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q})\boldsymbol{n}(\boldsymbol{q},\dot{\boldsymbol{q}})\right]\\ &\quad + \underbrace{\boldsymbol{M}(\boldsymbol{q})(\boldsymbol{I} - \boldsymbol{G}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q}))\boldsymbol{M}^{-1}(\boldsymbol{q})}_{\text{projection matrix in the dynamic null space of } \boldsymbol{J}}\underset{\substack{\uparrow \\ \text{arbitrary joint torque} \\ \text{available for reaction to collisions}}}{\boxed{\boldsymbol{\tau}_0}}\end{aligned}$$

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 always be decomposed as

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

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

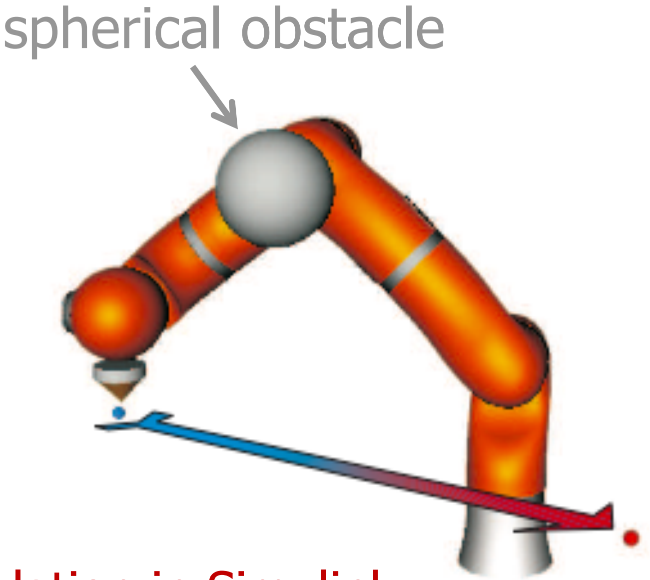
$$\begin{aligned} \boldsymbol{H}_M(\boldsymbol{q}) &= \left(\boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q})\boldsymbol{J}^T(\boldsymbol{q})\right)^{-1}\boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q}) \\ &=: \boldsymbol{\Lambda}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q}),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

$\boldsymbol{\Lambda}(\boldsymbol{q})$ is the effective Cartesian inertia!

- thus, the dynamically consistent solution is given by

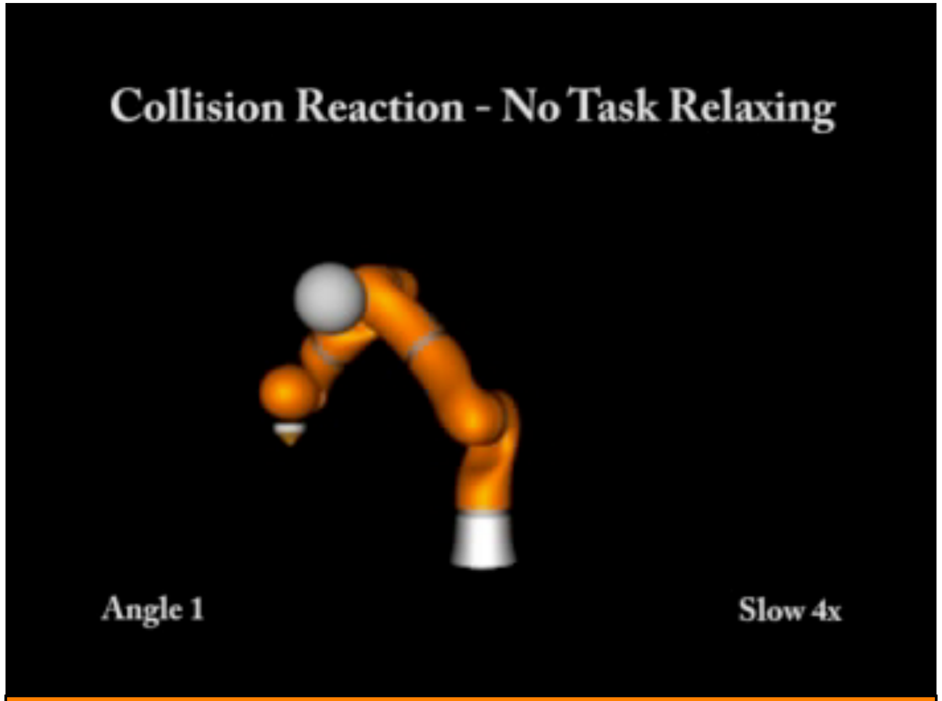
$$\boxed{\begin{aligned} \boldsymbol{\tau} = \; & \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{\Lambda}(\boldsymbol{q})(\ddot{\boldsymbol{x}} - \dot{\boldsymbol{J}}(\boldsymbol{q})\dot{\boldsymbol{q}} + \boldsymbol{J}(\boldsymbol{q})\boldsymbol{M}^{-1}(\boldsymbol{q})\boldsymbol{n}(\boldsymbol{q},\dot{\boldsymbol{q}}))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

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 (∝ 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

https://youtu.be/q4PZKE-kgc0

video @IROS 2017

Human-Robot Coexistence and Contact Handling with Redundant Robots

Emanuele Magrini
Alessandro De Luca

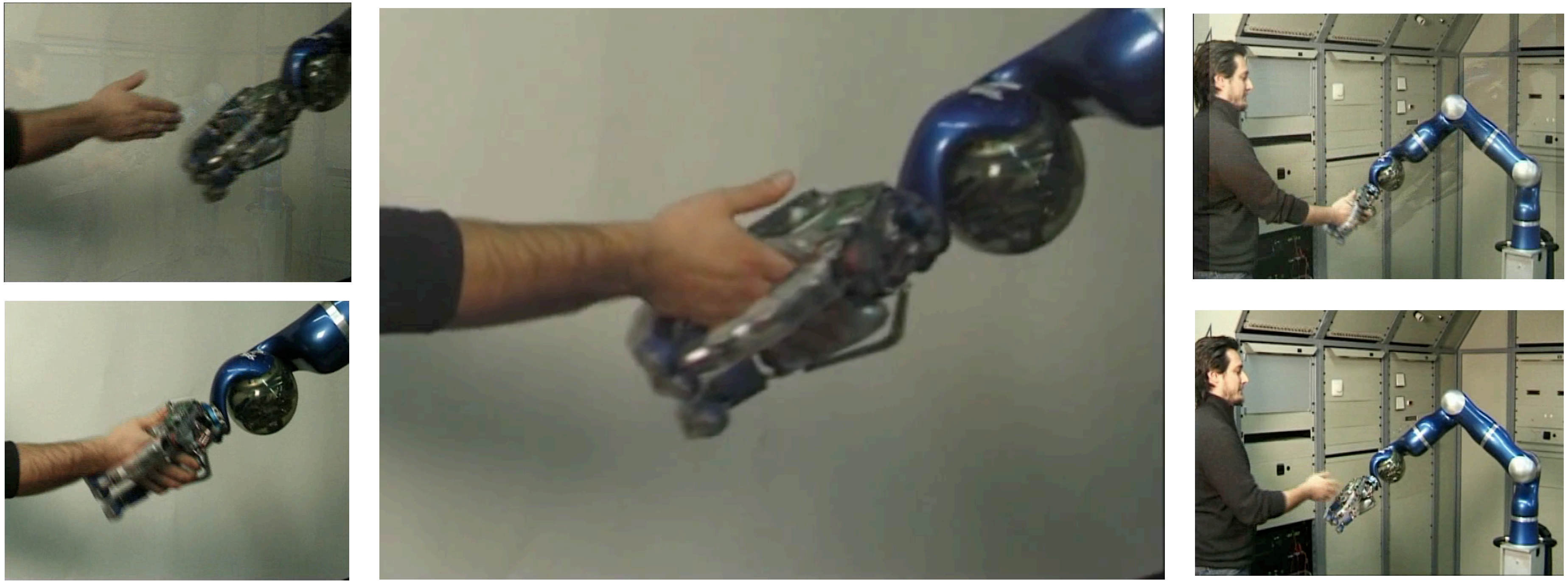
Robotics Lab, DIAG
Sapienza Università di Roma

February 2017

idle ⇔ relax ⇔ abort

Combined use

6D F/T sensor at the robot wrist + residuals



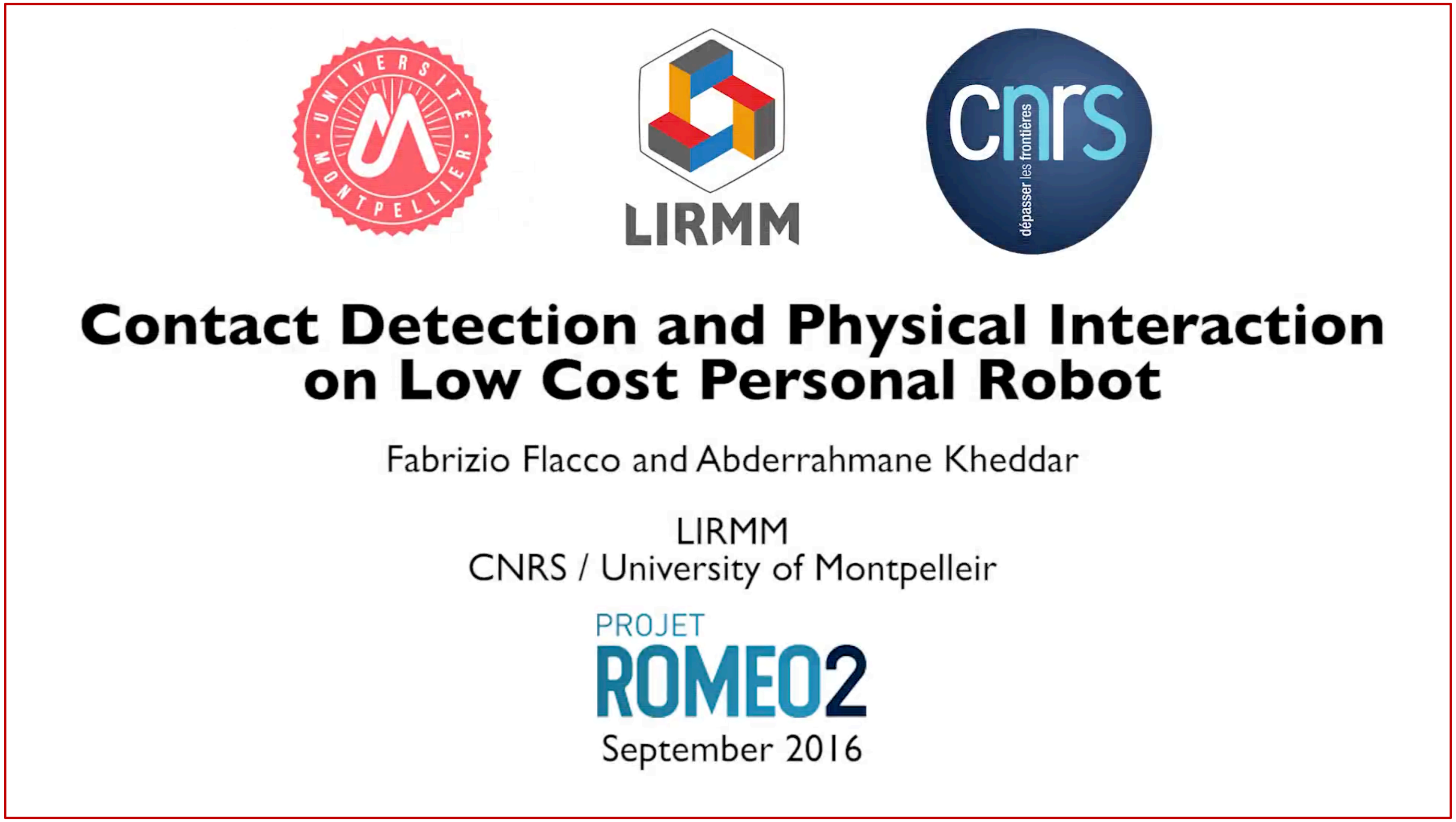
video

- include the F/T measures in the expression of the residual: $\boldsymbol{J}_{EE}^{T}(\boldsymbol{q})\boldsymbol{F}_{m}$
- may be used to distinguish intentional contacts vs. unexpected collisions
- ... but only at the end-effector level!
- in case of intentional contacts, what should a robot do other than react to contacts/collisions by stopping or escaping? ⇒ physical collaboration (pHRC)

pHRI in low-cost (humanoid) robots

forearm of the ROMEO personal robot

video



Contact Detection and Physical Interaction on Low Cost Personal Robot

Fabrizio Flacco and Abderrahmane Kheddar

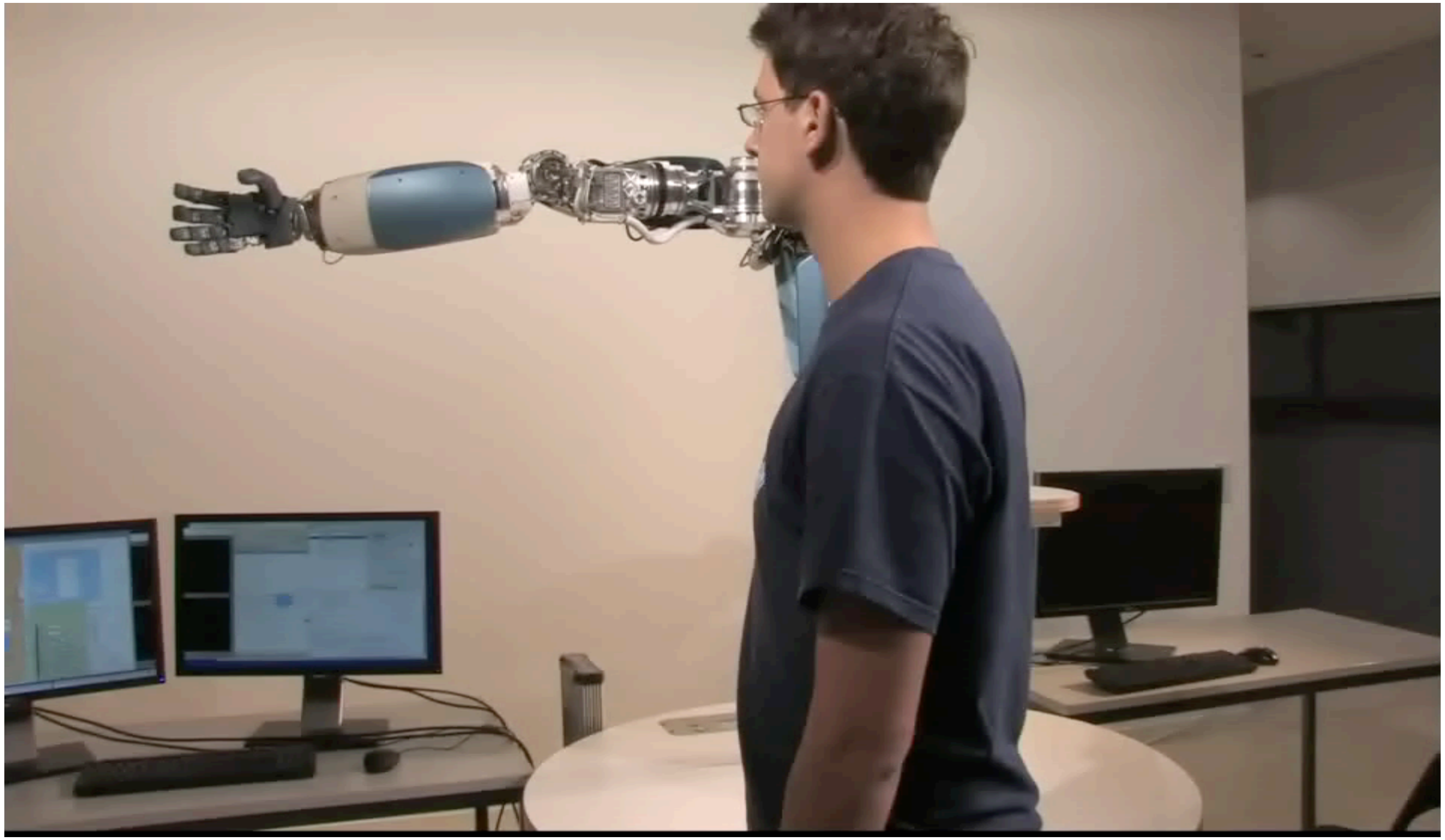
LIRMM
CNRS / University of Montpellier

PROJET
ROMEO2
September 2016

- the momentum-based residual method has been implemented worldwide in a large number of robotic systems (industrial robots, prototypes, VSA-based manipulators, …)
- a different computation of residuals is needed for “floating base” humanoids and UAVs

Collision detection and reaction

with full VSA-based DLR HASY robot

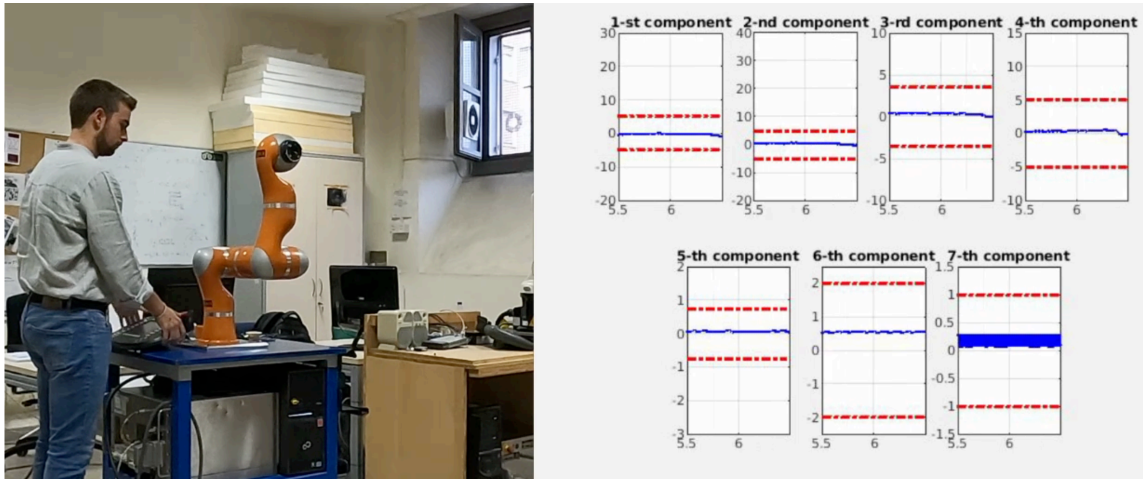


video

- with a momentum-based residual method

SAPHARI
Safe and Autonomous
Physical Human-Aware
Robot Interaction

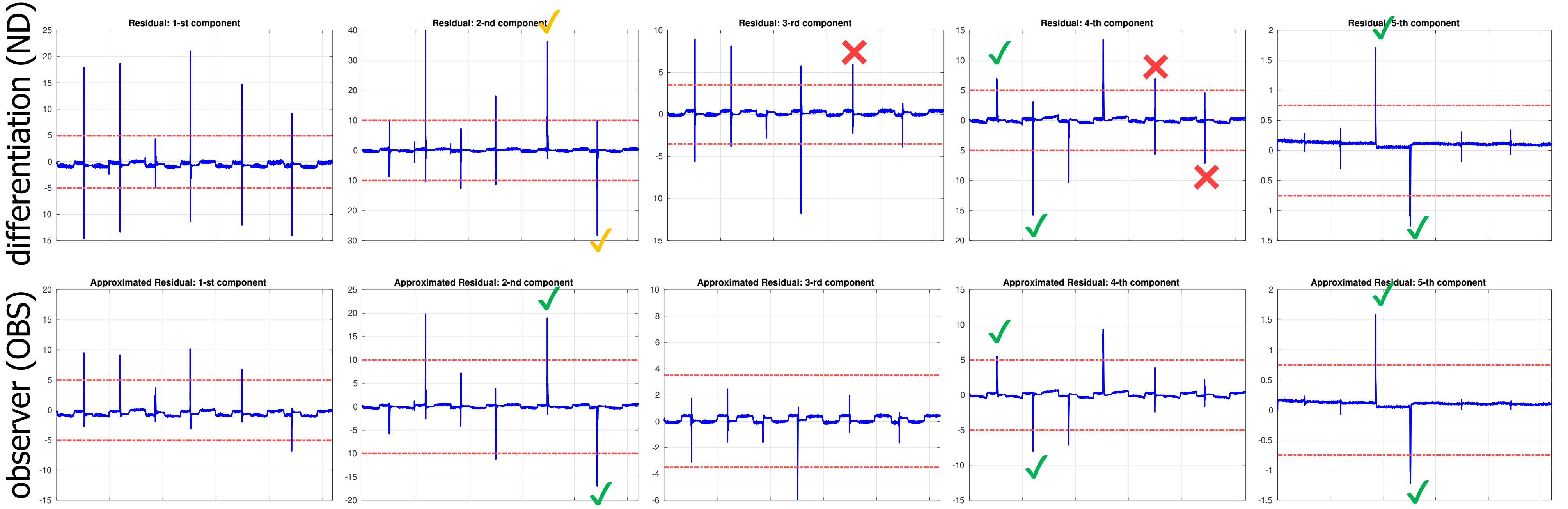
Collision detection and isolation
using a joint velocity observer in the residual



- numerical differentiation of encoders vs. dynamic reduced-order observer
- 6 link collisions in sequence (over 30 s):
  L4 (twice, ±) ⇒ L5 (twice, ±) ⇒ L2 (twice, ±)
- both methods detect collisions correctly
- ND has two false isolations (#5 and #6)
- OBS isolates the colliding link correctly

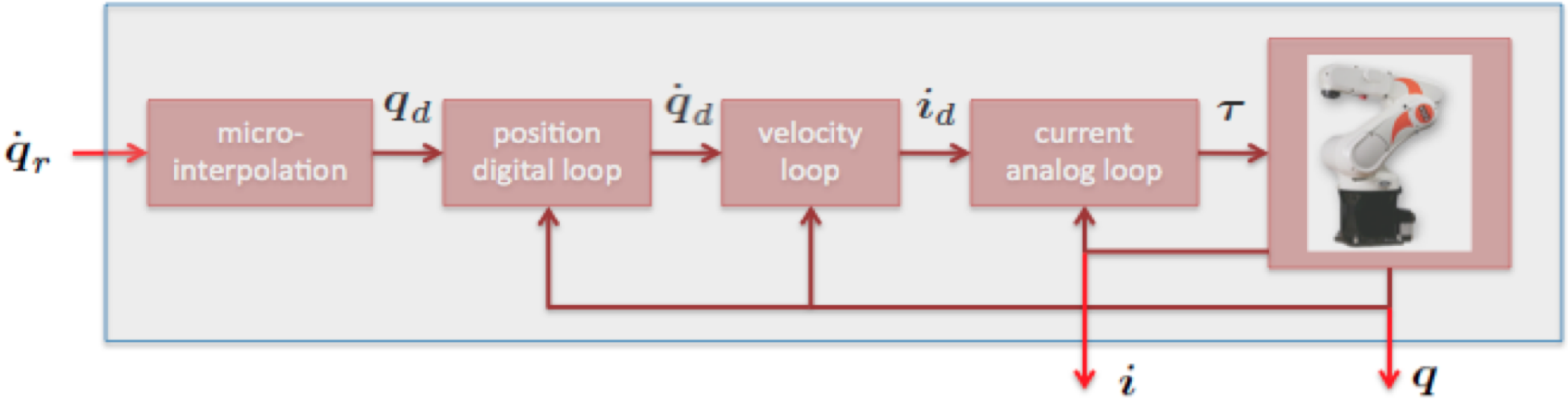
video

only first 5 residuals are shown (out of 7)

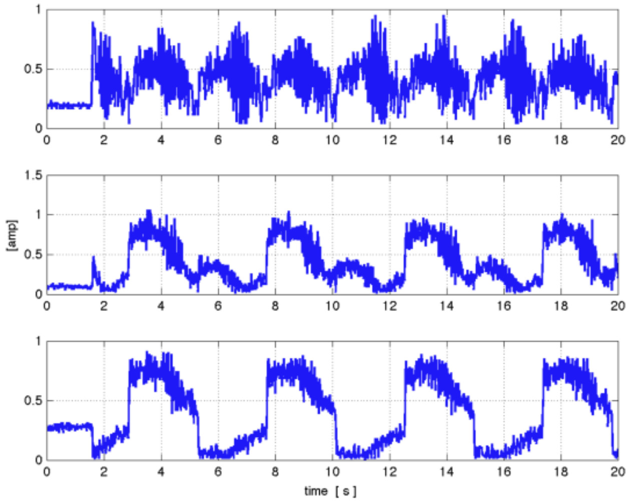


pHRI in closed control architectures

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)

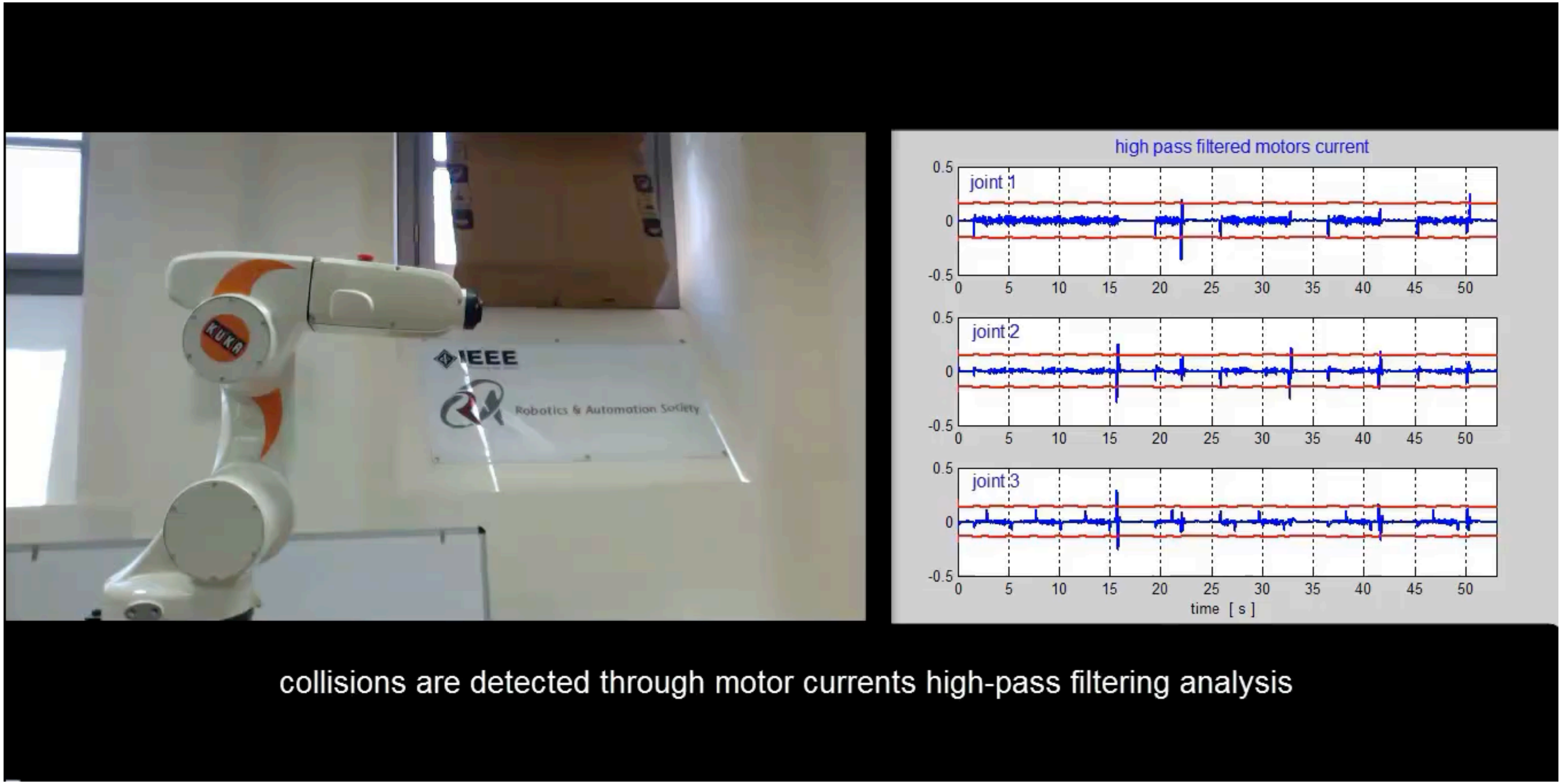


motor currents measured on first three joints

Collision detection and stop

https://youtu.be/18RsAxkf7kk

video @ICRA 2013



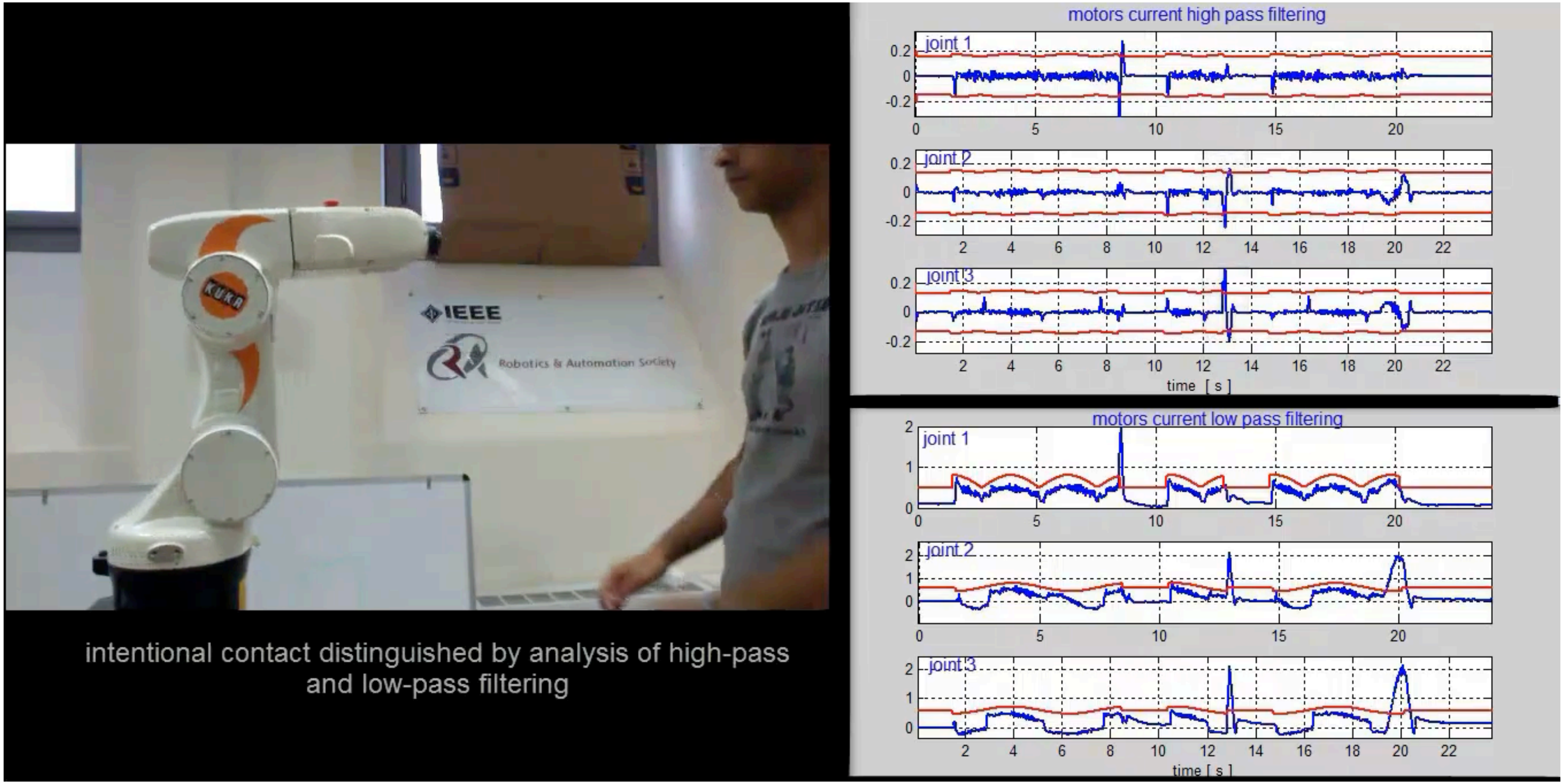
collisions are detected through motor currents high-pass filtering analysis

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

Collisions vs intentional contact

distinguish and then collaborate …

video @ICRA 2013


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

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

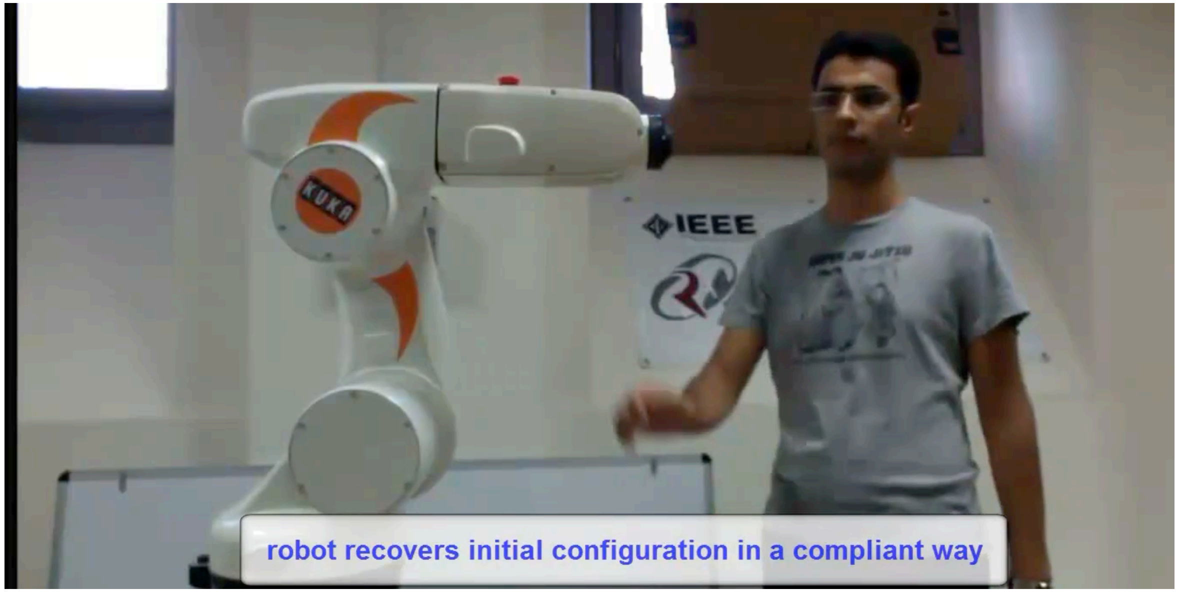
video
@ICRA
2013

collaboration mode

compliant-like
robot behavior

here, time-varying thresholds
based on the desired trajectory

… we are "control-cheating" a bit:
no torque command is ever issued!



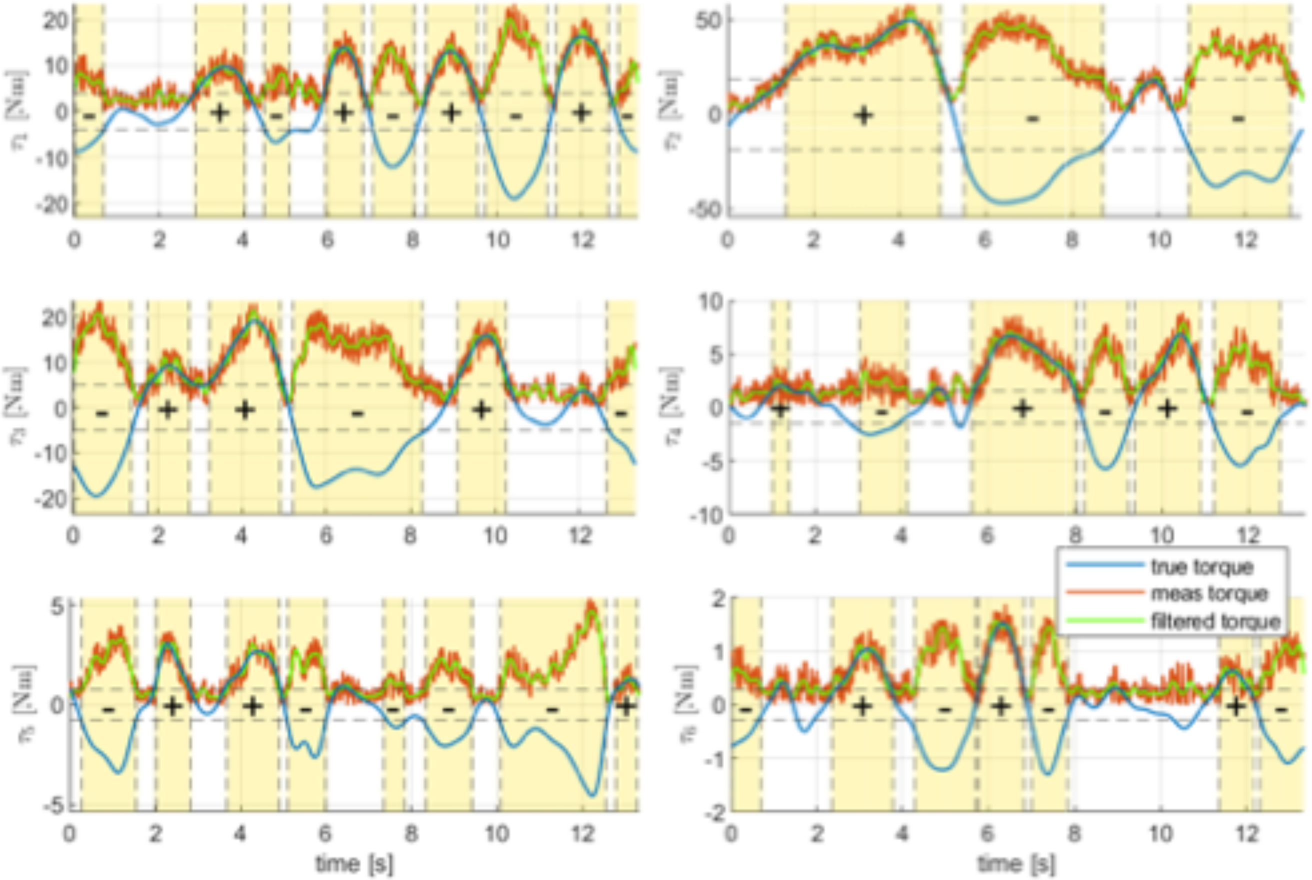
video
@ICRA
2013

Dynamic modeling

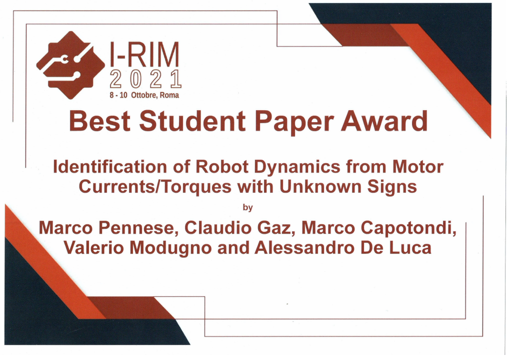
KUKA KR5 Sixx R650 robot (in 2021)

simulation
test

39/39 segments
of motor currents
correctly handled
(assign right +/-)



- identify signs of motor currents by means of a Tree Penalty-Based Parameter Retrieval algorithm
- use the method in experimental identification of robot dynamic model, followed by validation tests



I-RIM
2021
8 - 10 Ottobre, Roma

Best Student Paper Award

Identification of Robot Dynamics from Motor Currents/Torques with Unknown Signs

by

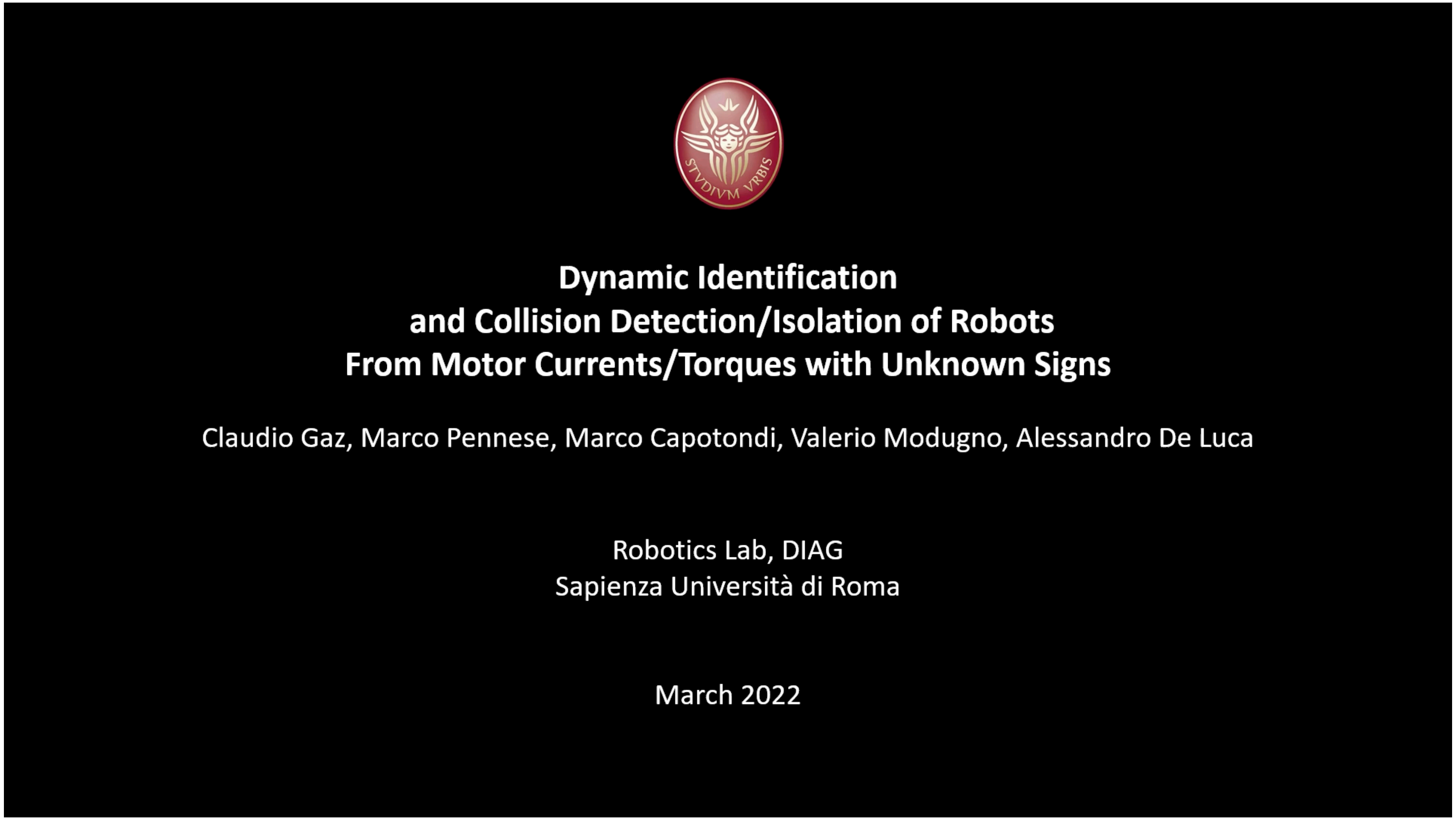
Marco Pennese, Claudio Gaz, Marco Capotondi, Valerio Modugno and Alessandro De Luca

Collision detection and isolation

KUKA KR5 Sixx R650 robot

video

$$\sigma_{mod}(t) = k_\sigma \int_0^t \left[\hat{\boldsymbol{\pi}}^T \boldsymbol{Y}^T(s)\boldsymbol{Y}(s)\hat{\boldsymbol{\pi}} - \boldsymbol{\tau}^T(s)\boldsymbol{\tau}(s) - \sigma_{mod}(s)\right] ds$$



Dynamic Identification
and Collision Detection/Isolation of Robots
From Motor Currents/Torques with Unknown Signs

Claudio Gaz, Marco Pennese, Marco Capotondi, Valerio Modugno, Alessandro De Luca

Robotics Lab, DIAG
Sapienza Università di Roma

March 2022

use of extra residuals for motor currents of a priori unknown signs

Further pHRI results

obtained within/beyond the SAPHARI project

- integrated control approach with
  - collision avoidance (using exteroceptive sensors)
  - collision detection (with residual methods, whenever safe coexistence 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

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Videos: YouTube channel RoboticsLabSapienza. Playlist: Physical human-robot interaction

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Reduced-order velocity observer for rigid robots

- for use in position-only feedback control laws and for collision detection/isolation
- nice to have the same first-order structure of a momentum-based residual
- should work in closed-loop or open-loop mode (with possibly unbounded velocity)

$$\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{z}} = \boldsymbol{\tau} - \boldsymbol{S}(\boldsymbol{q}, \hat{\dot{\boldsymbol{q}}})\,\hat{\dot{\boldsymbol{q}}} - \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{f}(\boldsymbol{q}, \hat{\dot{\boldsymbol{q}}}) - k_0\,\boldsymbol{M}(\boldsymbol{q})\hat{\dot{\boldsymbol{q}}}$$

$$\hat{\dot{\boldsymbol{q}}} = \boldsymbol{z} + k_0\,\boldsymbol{q}$$

Theorem 1. Assume that $\|\dot{q}\| \leq v_{max}$ is known. Then, for any fixed $\eta > 0$, by choosing

$$k_0 \geq (c_0 v_{max} + \eta)/\lambda_{min}(\boldsymbol{M}(\boldsymbol{q}))$$

we obtain **local exponential stability** of the observation error $\boldsymbol{\varepsilon} = \dot{\boldsymbol{q}} - \hat{\dot{\boldsymbol{q}}}$ with a region of attraction $\mathcal{E}(\eta)$

Theorem 2. Assume that $\limsup_{n\to\infty} \|\dot{q}\| \leq v$ exists but is yet unknown. Then, using a switching logic to adjust the gain with a hybrid dynamics scheme, we obtain **local exponential stability** of the observation error $\boldsymbol{\varepsilon} = \dot{\boldsymbol{q}} - \hat{\dot{\boldsymbol{q}}}$

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