*Robotics 2*

# Detection and isolation of robot actuator faults

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# Fault diagnosis problems - 1

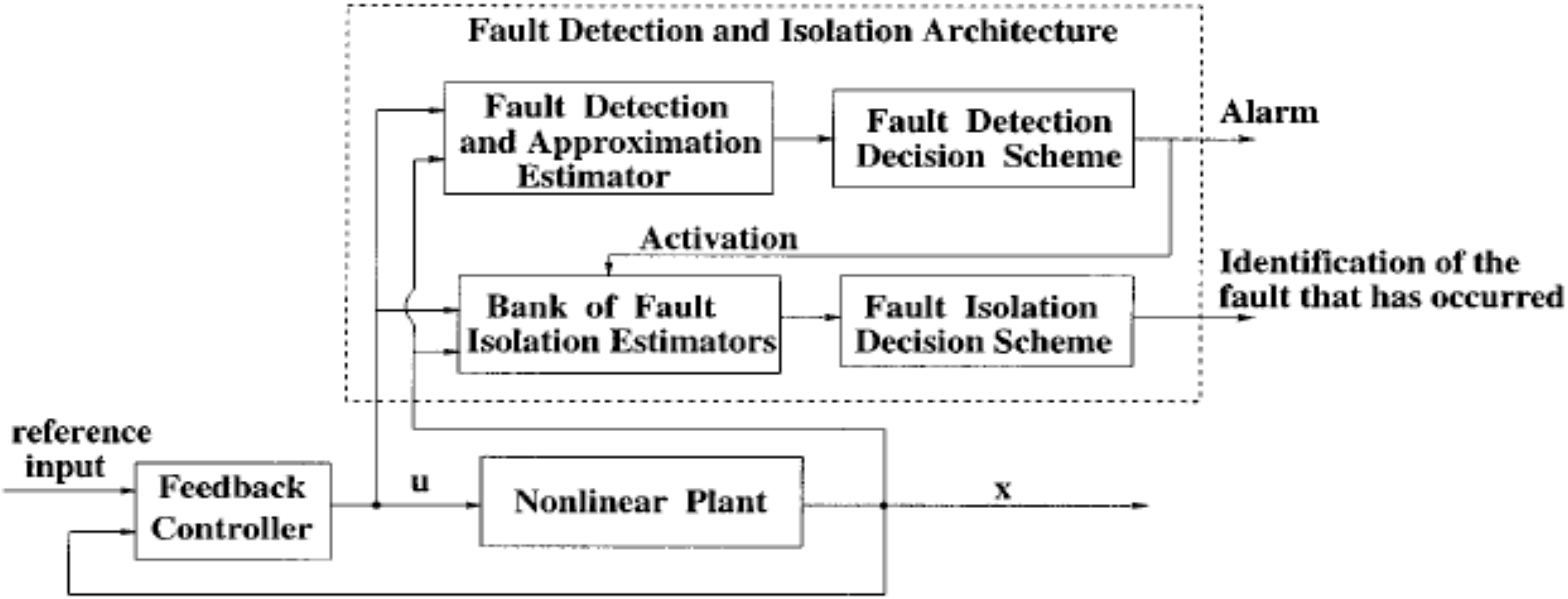
- in the diagnosis of faults possibly affecting a (nonlinear) dynamic system various problems can be formulated
- Fault Detection
  - recognize that the malfunctioning of the (controlled) system is due to the occurrence of a fault (or not proper behavior) affecting some physical or functional component of the system
- Fault Isolation
  - discriminate which particular fault $f$ has occurred out of a (large) class of potential ones, by distinguishing it from any other fault and from the effects of disturbances possibly acting on the system
- Fault Identification
  - determine the time profile (and/or class type) of the isolated fault $f$
- Fault Accommodation
  - modify the control law so as to compensate for the effects of the detected and isolated fault (possibly also identified)

# Fault diagnosis problems - 2

- FDI solution (simultaneous detection and isolation)
  - definition of an auxiliary dynamic system (Residual Generator) whose output will depend only on the presence of the fault $f$ to be detected and isolated (and not on any other fault or disturbance) and will converge asymptotically to zero when $f \equiv 0$ (stability)
  - in case of many potential faults, each component $r_i$ of the vector $r$ of residuals will depend on one and only one associated fault $f_i$ (possibly reproducing approximately its time behavior)
  - many of the FDI schemes are model-based: they use a nominal (fault- and disturbance-free) dynamic model of the system
- Fault Tolerant Control
  - passive: control scheme that is intrinsically robust to uncertainties and/or faults (typically having only moderate/limited effects)
  - active: control scheme involving a reconfiguration after FDI (with guaranteed performance for the faulted system)

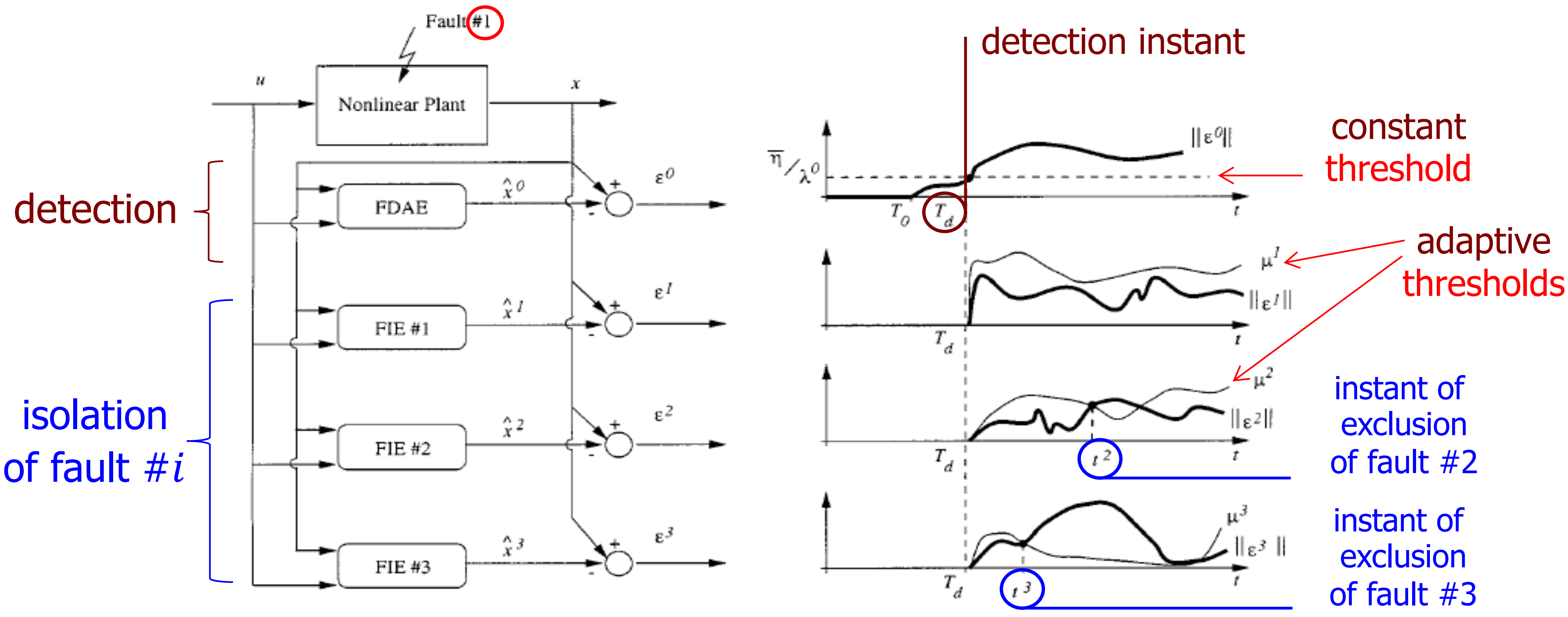
# Typical FDI architecture

- bank of $n + 1$ (model-based) estimators
  - 1 for detection of a faulty condition
  - $n$ for isolation of the specific (in general, modeled) fault



# Some terminology

- fault types
  - instantaneous (abrupt), incipient (slow), intermittent, concurrent
- thresholds for detection/isolation (also adaptive)
  - delay times (w.r.t. the instant $T_0$ of fault start) vs. false alarms



# Actuator faults in robots

$q \in \mathbb{R}^N$

actual torque

$$\underbrace{M(q)}_{\text{inertia matrix } (>0)}\ddot{q} + \underbrace{c(q,\dot{q})}_{\text{centrifugal and Coriolis}} + \underbrace{g(q)}_{\text{gravity}} + \underbrace{F_V\dot{q} + F_S\,\mathrm{sgn}(\dot{q})}_{\text{viscous and static friction}} = \overbrace{\underbrace{u}_{\text{actuation torques}} - u_f}^{\text{actual torque}}$$

inertia matrix $(> 0)$

centrifugal and Coriolis

gravity

viscous and static friction

actuation torques

vector of actuation faults (even concurrent on more axes)

- total fault $u_{f,i} = u_i$
- partial fault $u_{f,i} = \varepsilon u_i \;\; (0 < \varepsilon < 1)$
- saturation $u_{f,i} = u_i - \mathrm{sgn}(u_i)\, u_{i,max}$
- bias $u_{f,i} = b_i$
- block $u_{f,i} = \cdots$ ??
- ... any type!

# Working assumptions

- signals and measurements available
  - the commanded input torque $u$, but obviously not $u_f$ ...
  - a measure of the full state $(q, \dot{q})$ is available
    - can be relaxed: in practice, with an estimate of joint velocities
  - no further sensors are anyway necessary ("sensorless")
- the robot dynamic model is known
  - in the absence of faults, and neglecting disturbances
  - no pre-specified model or type of faults is needed
- no dependence on/request of a specific input $u(t)$
  - can be anything (open loop, linear or nonlinear feedback)
- no dependence on/request of a specific motion $q_d(t)$

# Generalized momentum

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

with associated dynamic equation

$$\boxed{\dot{p} = u - u_f - \alpha(q, \dot{q})}$$

decoupled components
relative to the single fault inputs

exploiting structure
of centrifugal and
Coriolis terms

$$\alpha_i = -\frac{1}{2}\dot{q}^T \frac{\partial M(q)}{\partial q_i}\dot{q} + g_i(q) + F_{V,i}\dot{q}_i + F_{S,i}\,\mathrm{sgn}(\dot{q}_i)$$

scalar expressions, for $i = 1, \cdots, N$

# FDI solution

- definition of a vector of residuals

$$r = K\left[\int (u - \alpha(q,\dot{q}) - r)dt \; - \; p\right]$$

$K > 0$ diagonal

- no need to compute joint accelerations nor to invert the robot inertia matrix $M(q)$
- with perfect model knowledge, the dynamics of $r$ is

$N$ decoupled filters, with unitary gains and time constants $\tau_i = 1/k_i$

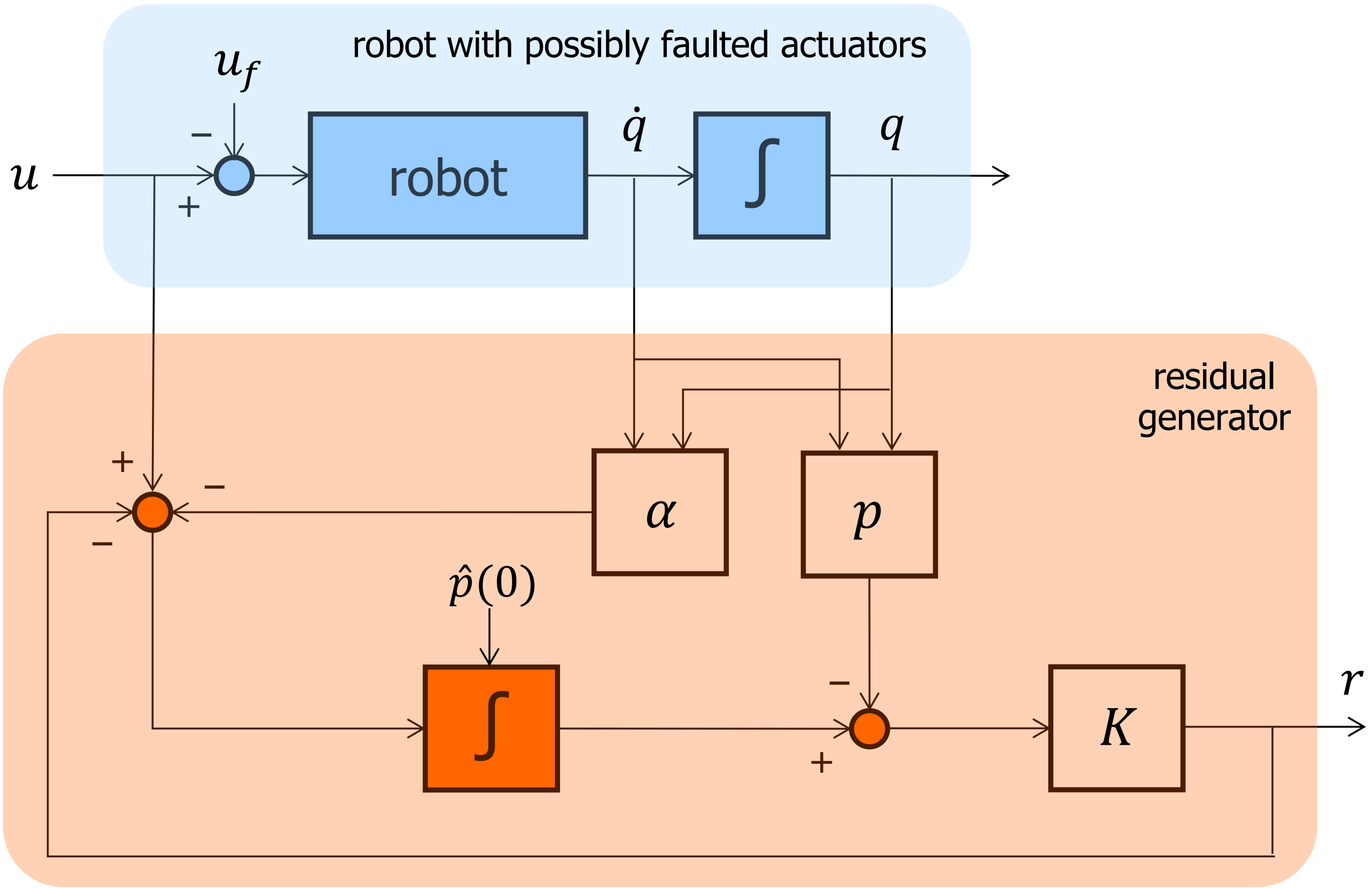
$$\dot{r} = -Kr + Ku_f$$

in the Laplace domain

$$\frac{r_i(s)}{u_{f,i}(s)} = \frac{k_i}{s + k_i} = \frac{1}{1 + \tau_i s}$$

for sufficiently large $K$, $r$ reproduces the time behavior of $u_f$

# Block diagram of the residual generator




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

$$r = K\left[\int (u - \alpha(q,\dot{q}) - r)dt \; - \; p\right]$$

# Residual generator as "disturbance observer"

from the block diagram…

$$\boxed{\begin{aligned}\dot{\hat{p}} &= u - \alpha(q,\dot{q}) + K(p - \hat{p})\\ r &= K(\hat{p} - p)\end{aligned}}$$

$\Updownarrow$

dynamic observer of the unknown actuation faults
($r \approx\rightarrow u_f$ = external disturbances)
with linear error dynamics (for constant $u_f$)

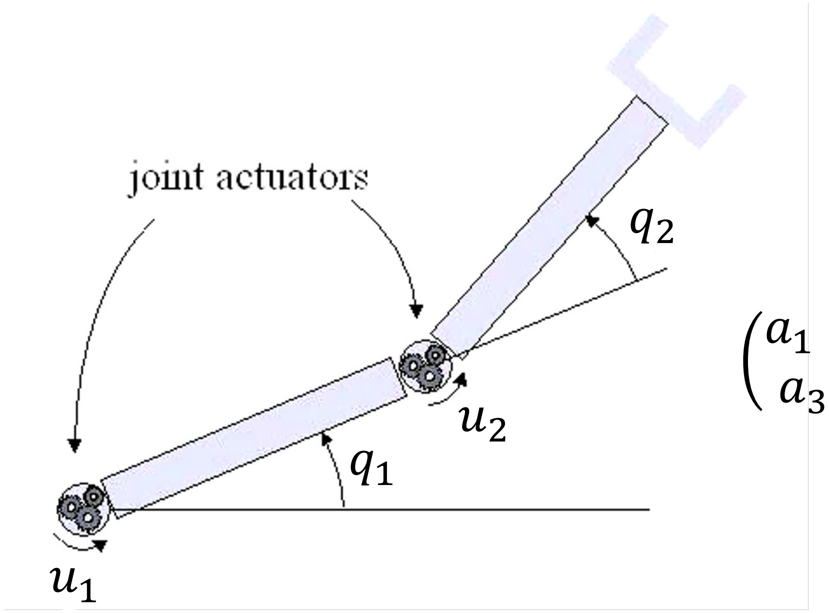
$e_{obs} = u_f - r \quad \Rightarrow \quad \dot{e}_{obs} = \dot{u}_f - \dot{r} = \dot{u}_f - K(\dot{\hat{p}} - \dot{p})$

$$= \dot{u}_f - K\big((u - \alpha - r) - (u - \alpha - u_f)\big)$$

$$= \dot{u}_f - K(u_f - r) = \dot{u}_f - K e_{obs} \cong -K e_{obs}$$

# A worked-out example

- planar 2R robot under gravity




dynamic model (without friction)

$$M(q)\ddot{q} + \underbrace{c(q,\dot{q})}_{= S(q,\dot{q})\dot{q}} + g(q) = u - u_f$$

$$\begin{pmatrix} a_1 + 2a_2c_2 & a_3 + a_2c_2 \\ a_3 + a_2c_2 & a_3 \end{pmatrix}\begin{pmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{pmatrix} + \begin{pmatrix} -a_2(2\dot{q}_1 + \dot{q}_2)\dot{q}_2 s_2 \\ a_2\dot{q}_1^2 s_2 \end{pmatrix}$$

$$+ \begin{pmatrix} a_4c_1 + a_5c_{12} \\ a_5c_{12} \end{pmatrix} = \begin{pmatrix} u_1 - u_{f,1} \\ u_2 - u_{f,2} \end{pmatrix}$$

computation of the residual vector

$$r = K\left[\int (u - \alpha(q,\dot{q}) - r)dt \; - \; p\right]$$

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

$$\alpha_1 = g_1(q) = a_4c_1 + a_5c_{12}$$

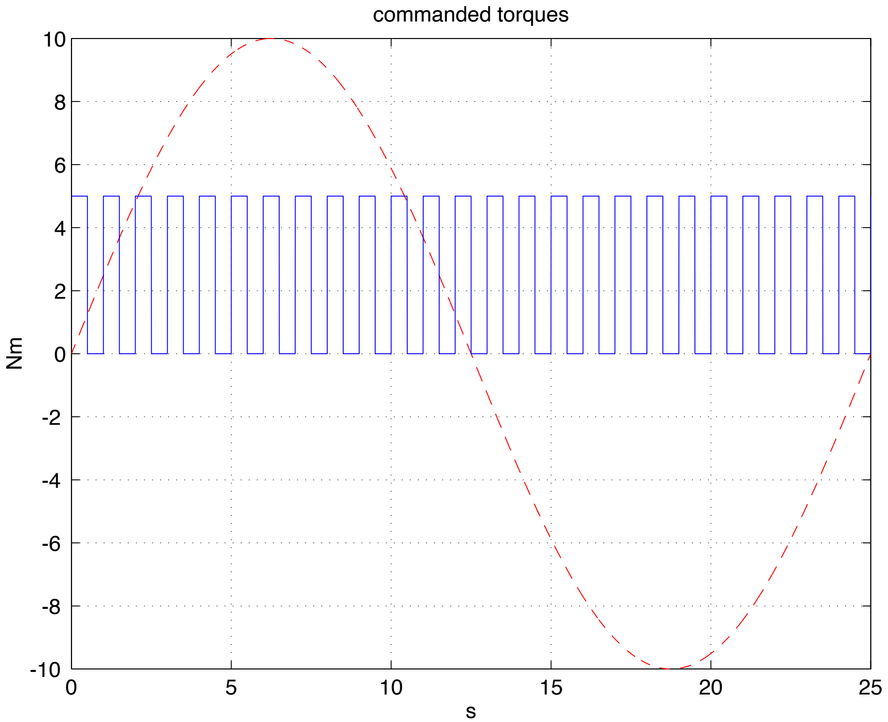
$$\alpha_2 = -\frac{1}{2}\dot{q}^T\frac{\partial M(q)}{\partial q_2}\dot{q} + g_2(q)$$

$$= a_2(\dot{q}_1 + \dot{q}_2)\dot{q}_1 s_2 + a_5c_{12}$$

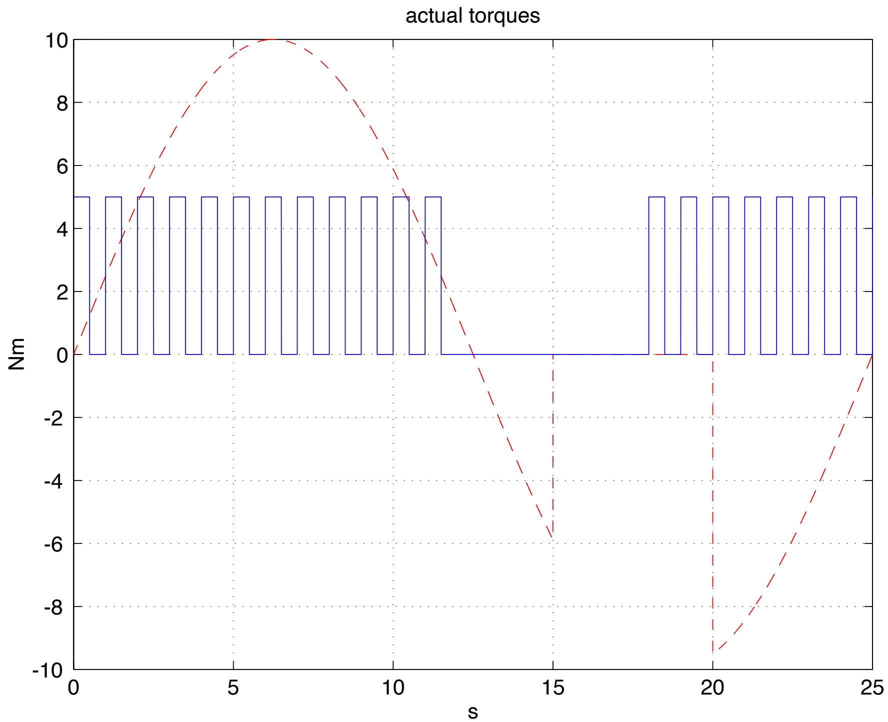
# Faults on both actuators

## (total, intermittent, concurrent)

commanded torques (in open loop)




actual (faulted) torques




= first joint (fault for $t \in [15 \div 20]$ sec)

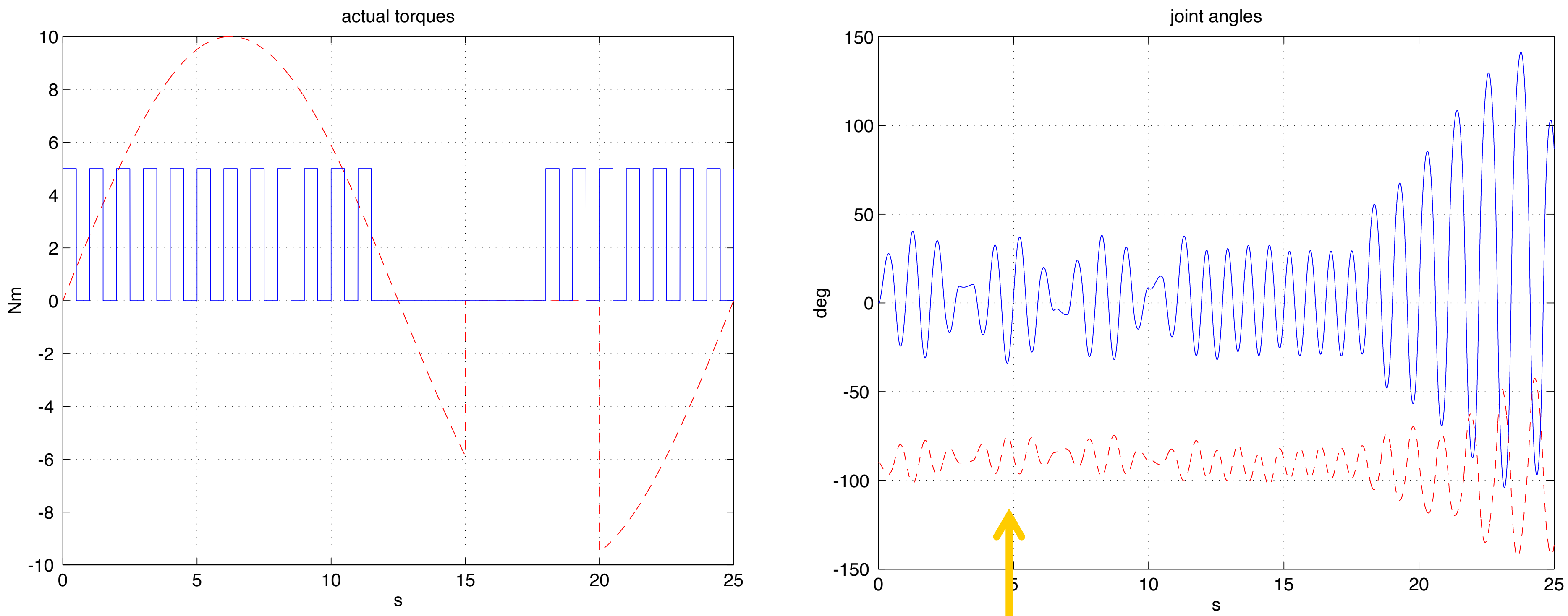
= second joint (fault for $t \in [12 \div 18]$ sec)

time interval of fault concurrence $t \in [15 \div 18]$ sec

# First simulation

actual torques (to the robot)

(measured) joint positions




= first joint

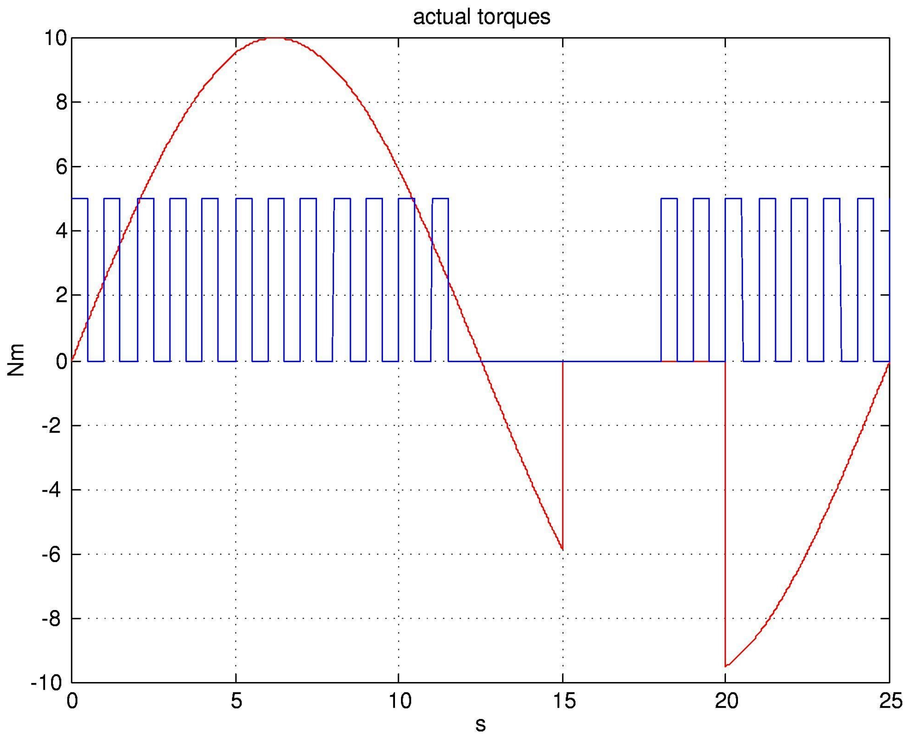
= second joint

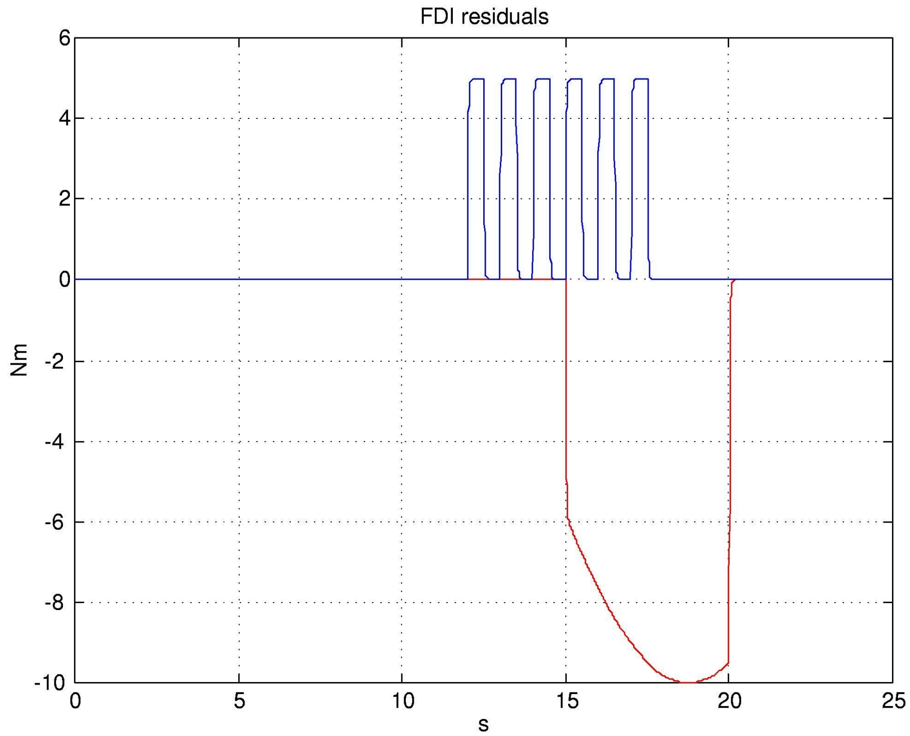
no clear evidence of faults in the dynamic evolution of the system!

# First simulation – FDI

actual torques (to the robot)

residuals




= first joint

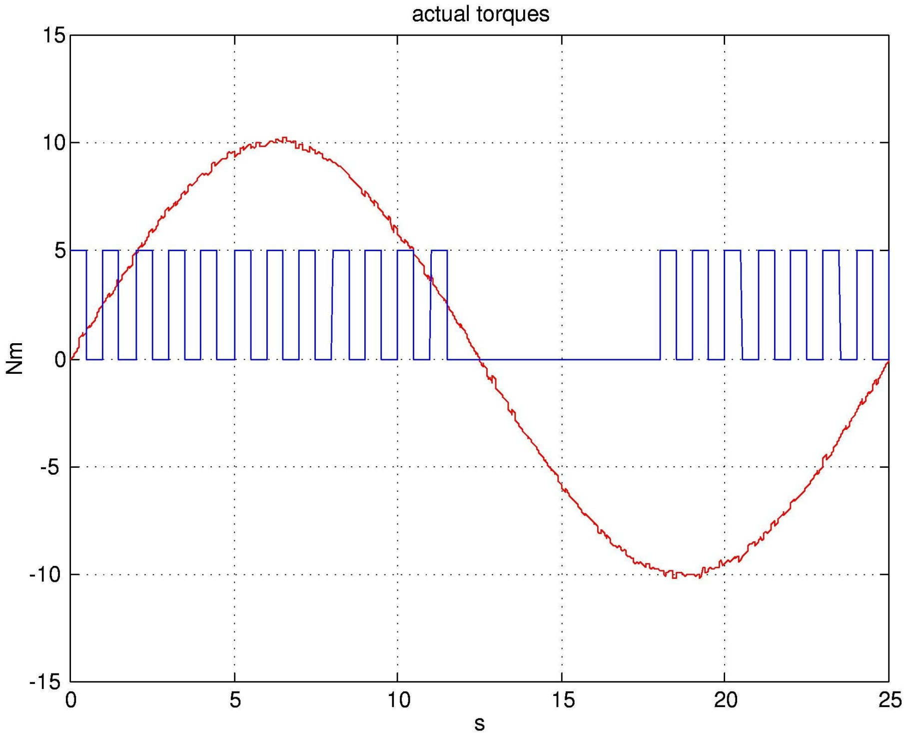
= second joint

$$K = \mathrm{diag}\{50, 50\}$$

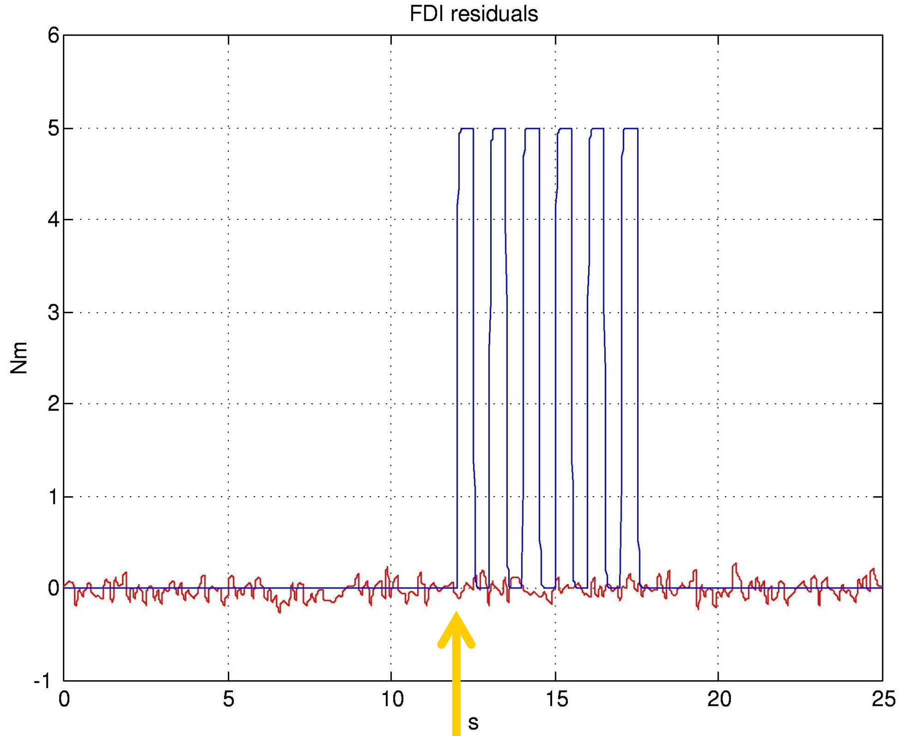
residuals reconstruct the "missing" parts of the torques (identification property!)

# Second simulation – FDI
## (total fault on second actuator, added noise on first channel)

actual torques (to the robot)




residuals




= first joint

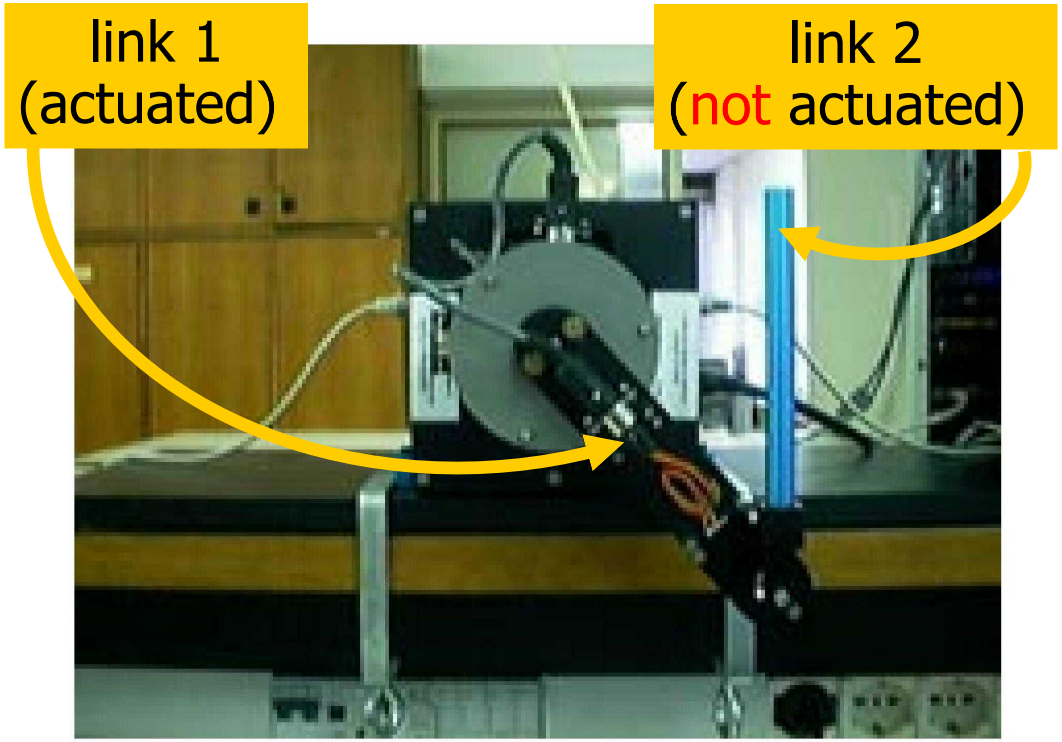
= second joint (fault for $t \in [12 \div 18]$ sec)

residual $r_1$ is not affected by faulty actuation, while residual $r_2$ is not affected by the disturbance on first channel (decoupling property)

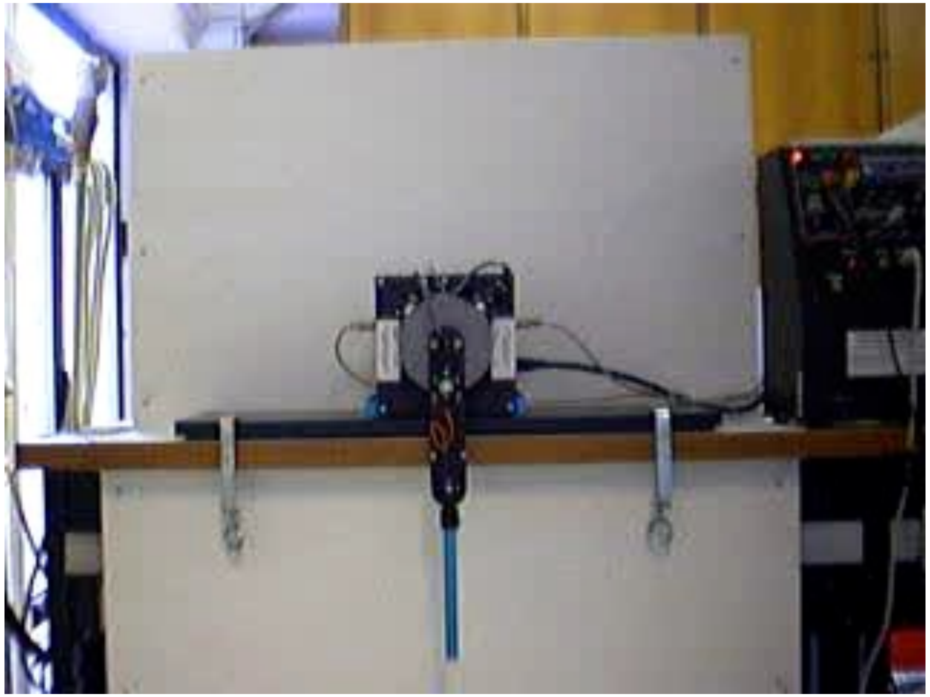
# Experimental setup

## Quanser Pendubot

video




with encoders on both joints



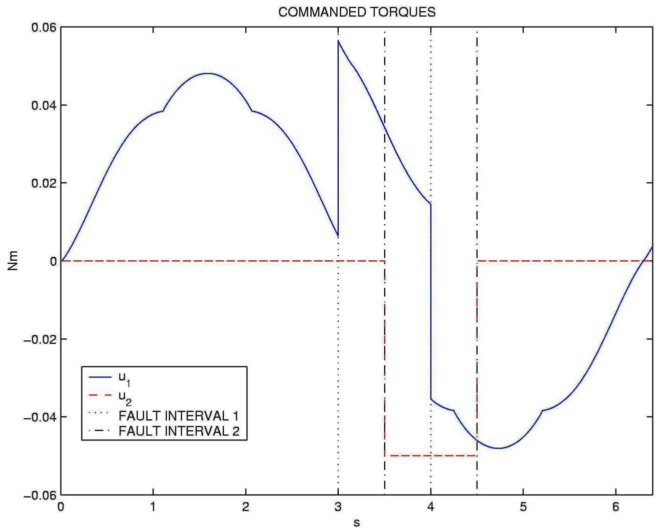
nonlinear control for swing-up

sampling time $T_c = 1$ ms, residual gains $K_i = 50$,
practical thresholds of fault detection $\cong 10^{-2} \div 10^{-3}$ Nm

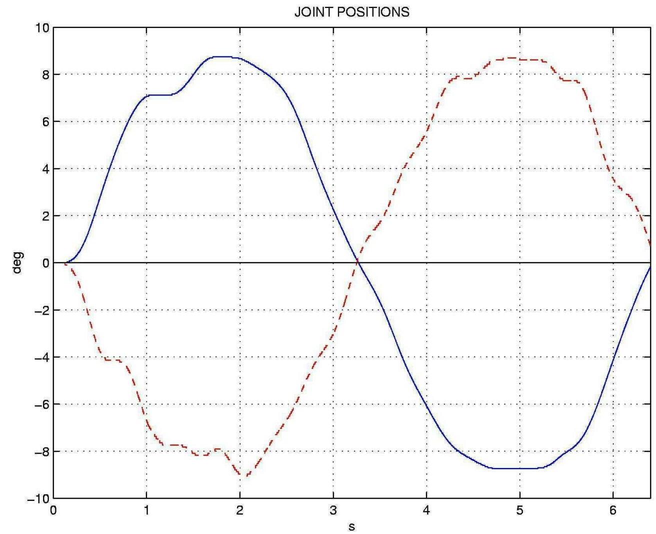
# First experiment

- motor 1 driven by sinusoidal voltage of period $2\pi$ sec (open loop)
- bias fault on $u_1$ for $t \in [3 \div 4]$ sec
- total fault on second joint for $t \in [3.5 \div 4.5]$ sec (a constant torque is requested, but no motor at the joint to provide 0.05 Nm…)
- fault concurrency for $t \in [3.5 \div 4]$ sec

commanded torques




joint positions



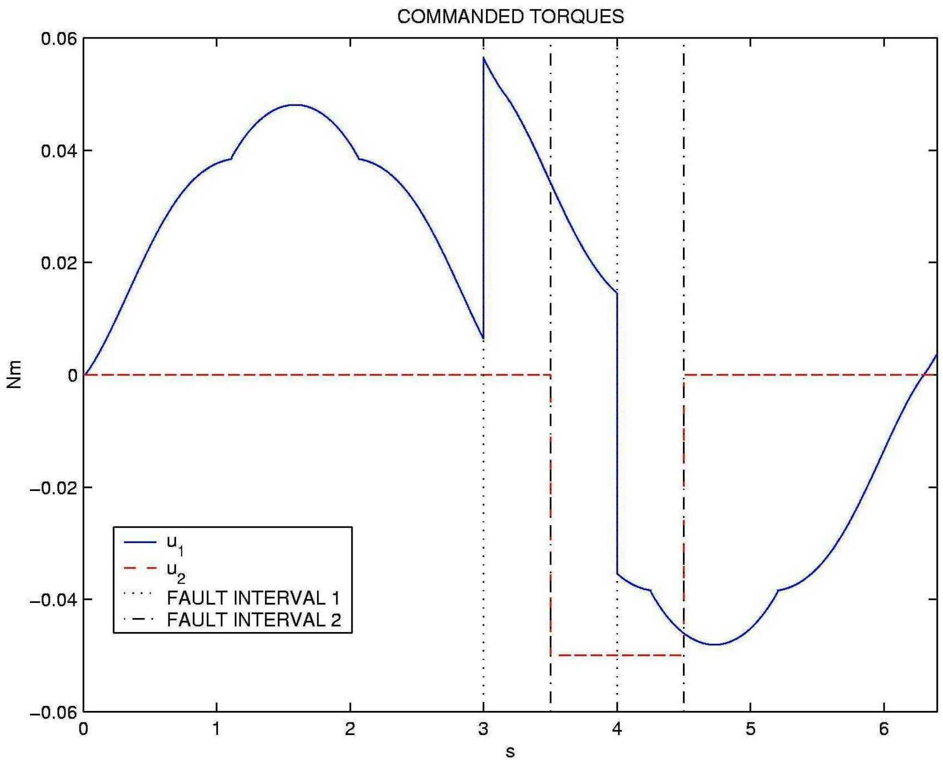

joint 1

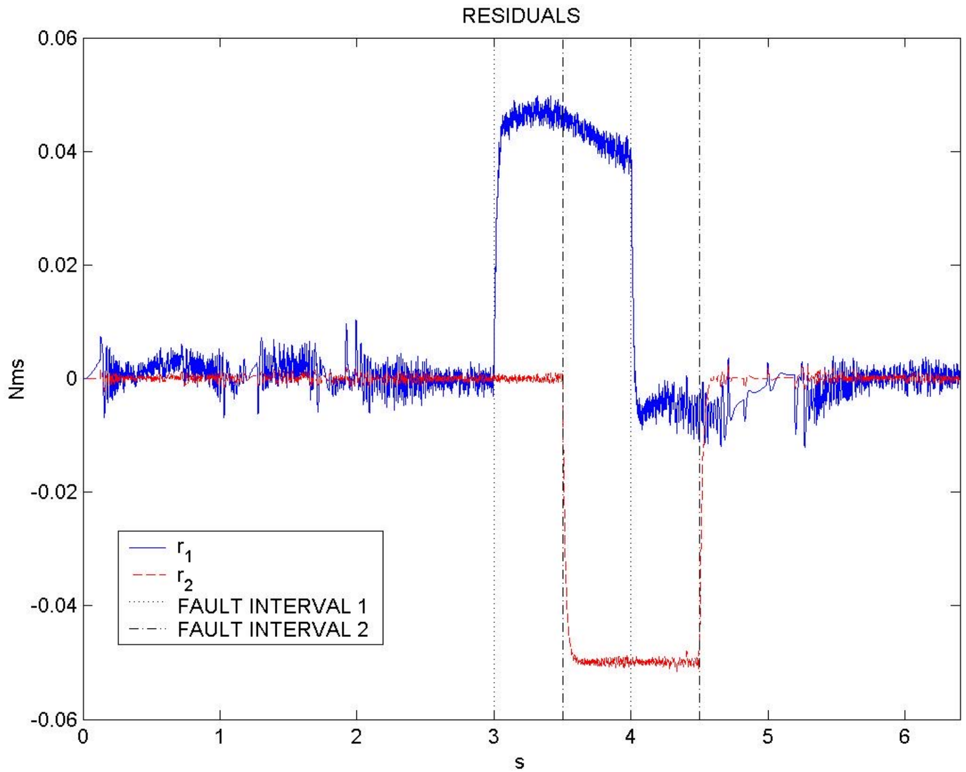
joint 2

# First experiment – FDI

commanded torques

residuals



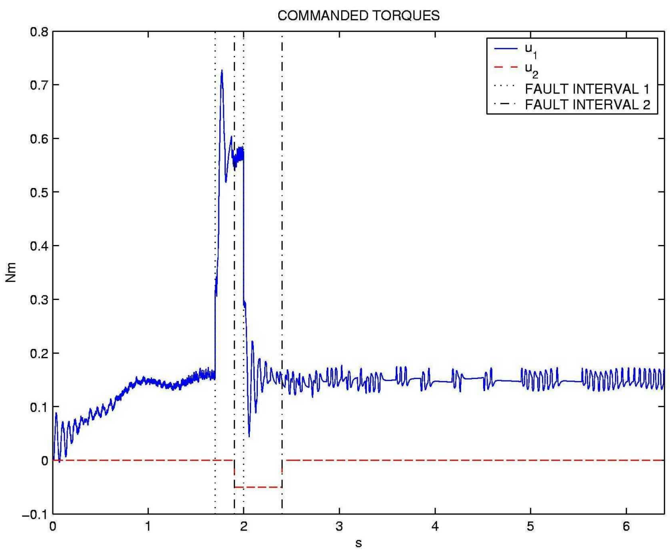




joint 1 — joint 2

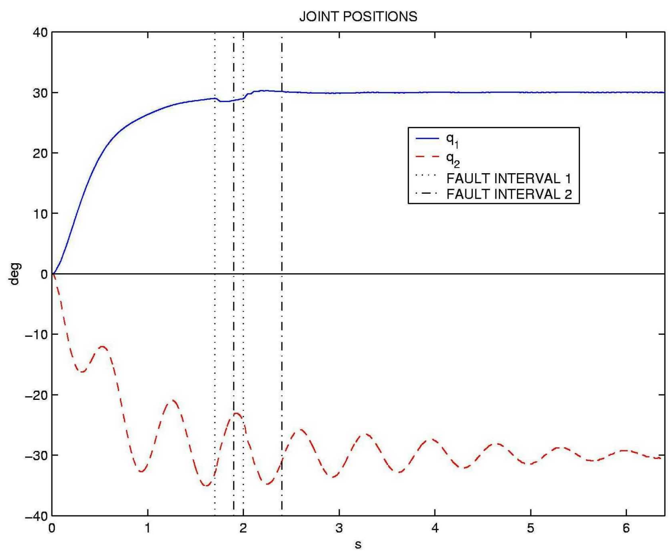
# Second experiment

- position regulation of the first joint at $q_{d1} = 30°$ (PID control)
- 50% power loss on motor 1 for $t \in [1.7 \div 2]$ sec
- total fault on joint 2 for $t \in [1.9 \div 2.4]$ sec (no motor…)
- fault concurrency for $t \in [1.7 \div 1.9]$ sec

commanded torques




joint positions

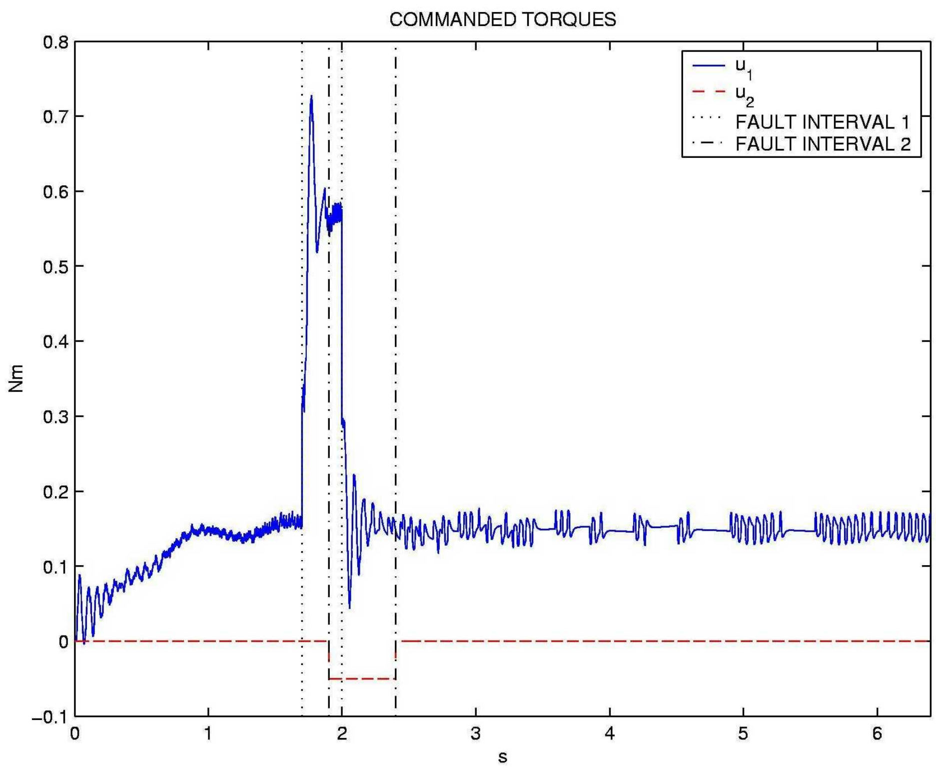


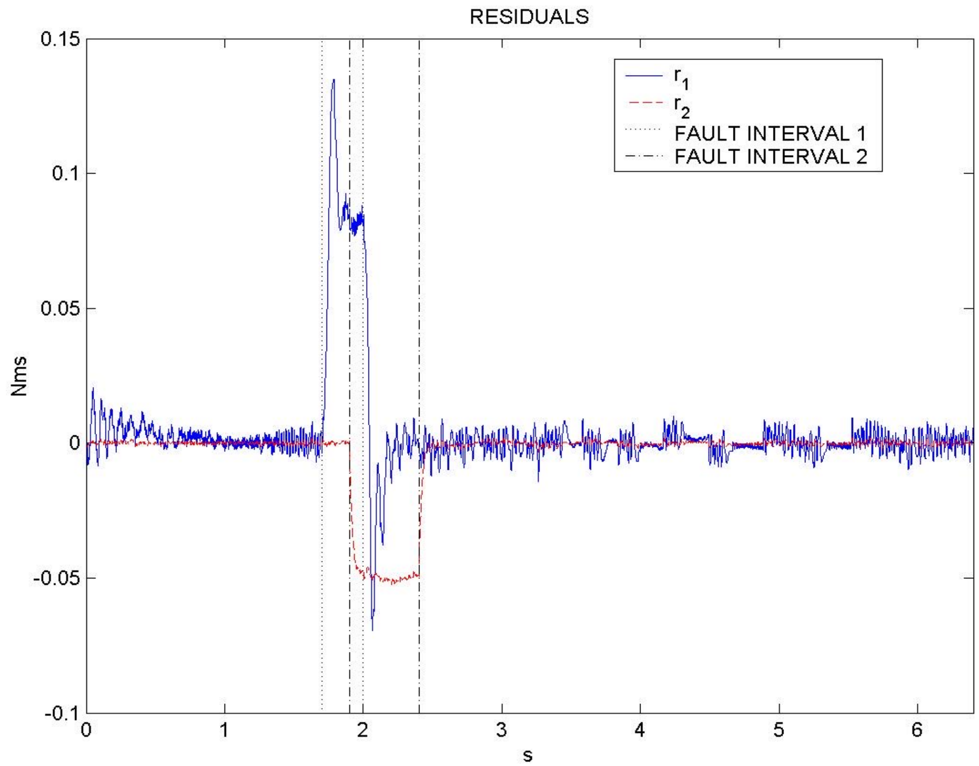

joint 1 joint 2

# Second experiment – FDI

commanded torques

residuals




joint 1 joint 2

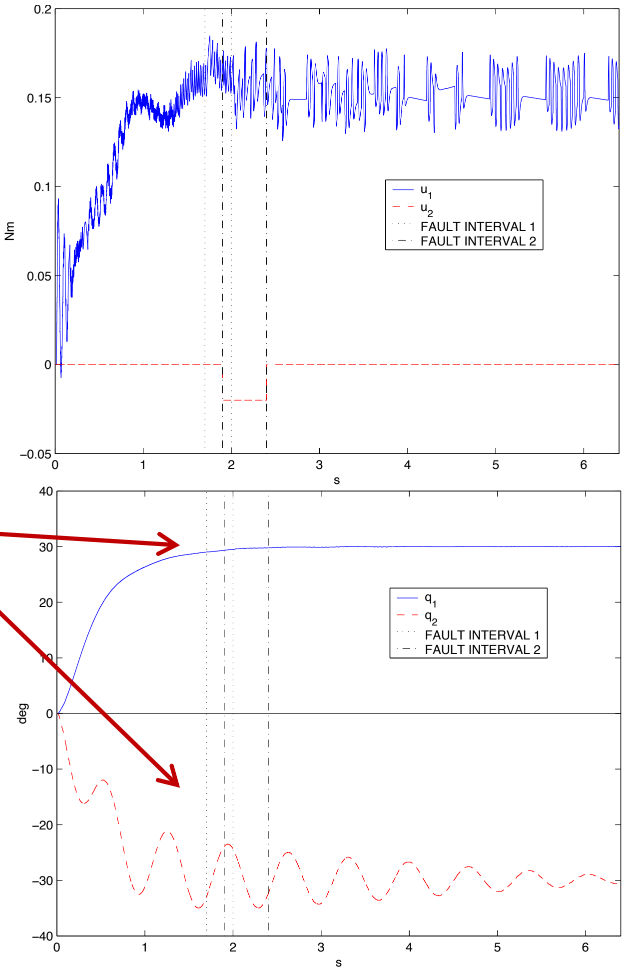
# Third experiment – FDI

- same as in second experiment, but with only 10% power loss on motor 1
  - due to noisy PWM signals driving the DC motor, a dynamic filtering of residuals is used, staying above [below] a threshold ($r_{1,thres} = 9 \cdot 10^{-3}$ Nm, $r_{2,thres} = 2 \cdot 10^{-3}$ Nm) for a time $T_{set} = 0.02$ s [$T_{reset} = 0.03$ s] before detecting a fault [reset to normal operation]

commanded torques

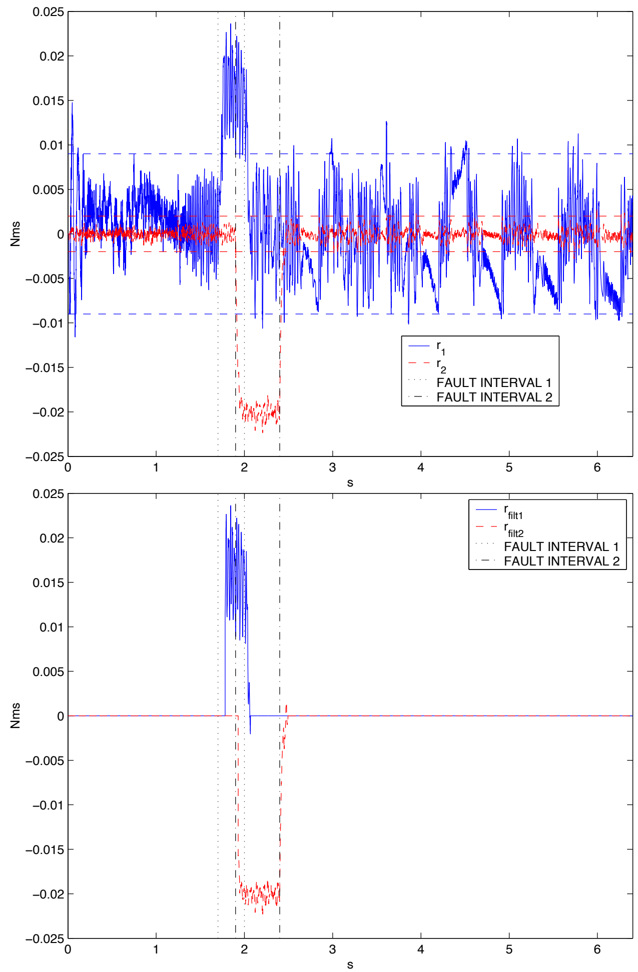
faults are "unobservable" in these evolutions

joint positions




joint 1

joint 2




residuals

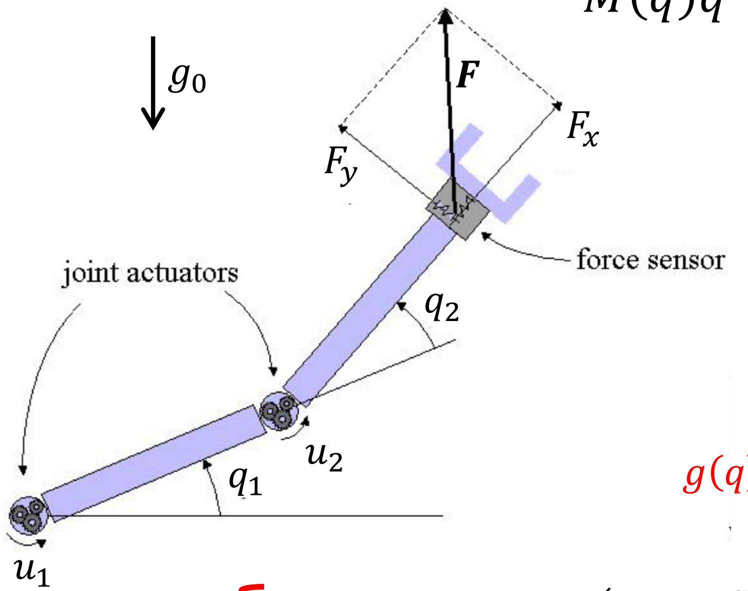
filtered residuals

# Some extensions

- FDI method based on generalized momentum is easily extended to the presence of flexible transmissions (elastic joints), actuator dynamics, …
- the scheme can be made adaptive, in order to handle parametric uncertainties in the robot dynamic model
- the method can be modified for detection and isolation of significant classes of sensor faults (e.g., faults in force/torque sensor at the wrist)
  - applies to all faults that instantaneously affect robot acceleration or torque (i.e., occurring at the second-order differential level)
- assuming non-concurrency (at most a single fault occurs at the same time) of a given set of faults, relaxed FDI conditions have been derived
  - of interest when the necessary conditions for multiple FDI are violated
  - involves processing of continuous residuals + discrete logic for isolation
- the same FDI-type approach has been applied also for compensation of unmodeled friction (treated as a "permanent fault" on the system)
- combination of model- and signal-based approaches to FDI

# Isolation of F/T sensor faults

- planar 2R robot with fault on force measure of sensor on the end-effector




$$M(q)\ddot{q} + S(q,\dot{q})\dot{q} + g(q) = u + J^T(q)F = u + J^T(q)(F_m + f_F)$$

$$J(q) = \begin{pmatrix} \ell_1 s_2 & 0 \\ \ell_2 + \ell_1 c_2 & \ell_2 \end{pmatrix}$$

robot Jacobian expressed in end-effector frame

$$J^{ad}(q) = \begin{pmatrix} \ell_2 & 0 \\ -\ell_2 - \ell_1 c_2 & \ell_1 s_2 \end{pmatrix}$$

adjoint of Jacobian $J^{ad} = \det(J) \cdot J^{-1}$ ⇒ singularity robust!

$g(q) - S^T(q,\dot{q})\dot{q}$ | time derivative of transposed Jacobian adjoint | robot inertia | input torque

residual generator (function of $q, \dot{q}, F_m, \zeta$)

$$\begin{cases} \dot{\zeta} = -(J^T)^{ad}(q)\begin{pmatrix} a_4 c_1 + a_5 c_{12} \\ a_5 c_{12} + a_2 s_2 \dot{q}_1(\dot{q}_1 + \dot{q}_2) \end{pmatrix} + \begin{pmatrix} 0 & \ell_1 s_2 \dot{q}_2 \\ 0 & \ell_1 c_2 \dot{q}_2 \end{pmatrix} M(q)\dot{q} + (J^T)^{ad}(q)u \\ \qquad + \ell_1 \ell_2 s_2 F_m + K[(J^T)^{ad}(q)M(q)\dot{q} - \zeta] \\ r = (J^T)^{ad}(q)M(q)\dot{q} - \zeta \end{cases}$$

$\det J^T(q)$ | measured force (nominal)

predicted FDI behavior in presence of force sensor faults $f_F \in \mathbb{R}^2$

$$\boxed{\dot{r} = -Kr + \ell_1 \ell_2 \sin q_2 \, f_F}$$

decoupled, though modulated by $q_2$

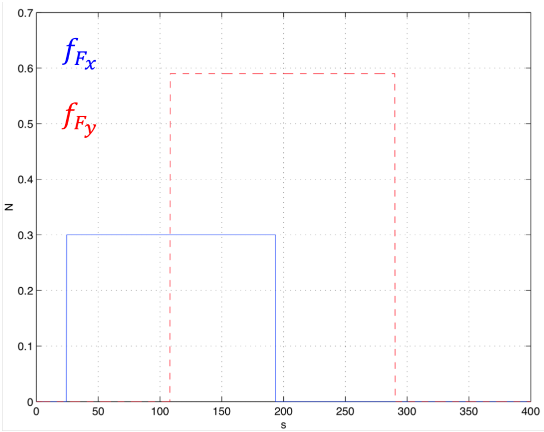
Ex: prove this expression!

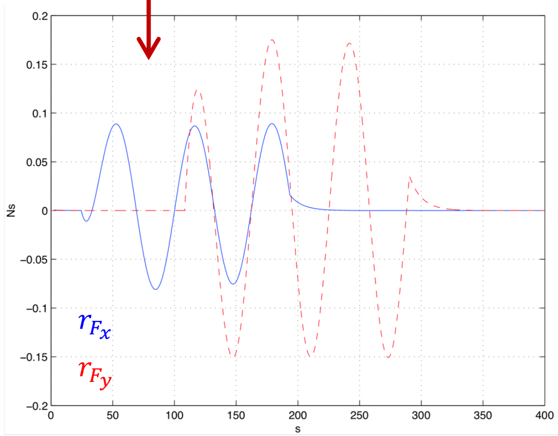
# Isolation of F/T sensor faults

- simulation on the 2R robot

$q_2$ is tracking a sinusoid ($A = \pi/8$ rad, $\omega = 0.1$ rad/s)

bias faults
on the two components
of force sensor measures
0.3N on $f_{F_x}$ in $t \in [25 \div 190]$
0.6N on $f_{F_y}$ in $t \in [109 \div 285]$

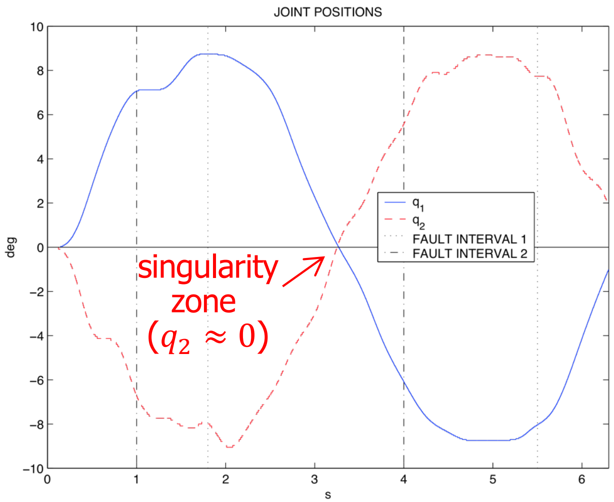


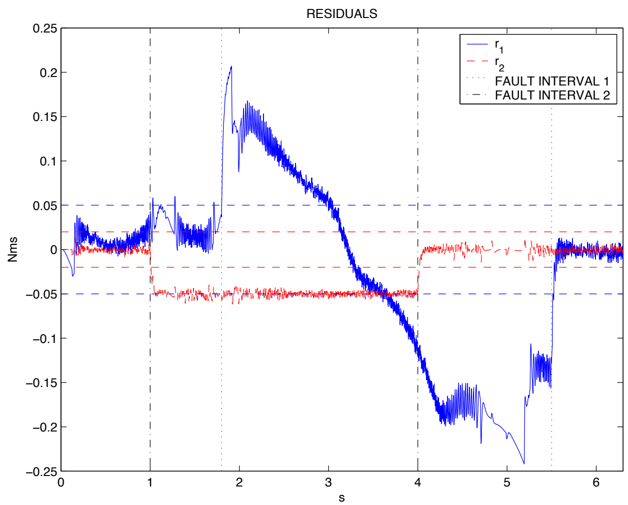




FDI residual
components
(with $K = 0.1I$)

- experiment on the Pendubot (no force sensor and no contact!)

evolution
of joint
variables




residuals
for emulated bias
measurement faults
-1N on $F_x$ in $t \in [1.8 \div 5.5]$
0.05N on $F_y$ in $t \in [1 \div 4]$

$(J^T)^{ad} \longrightarrow \text{diag}\{s_2, 1\}\, J^{-T}$
in previous scheme

# Isolation of non-concurrent faults

- faults of the actuators AND faults of the force sensor components (possibly occurring simultaneously) CANNOT be detected AND isolated
  - for a mechanical system with $N$ dofs, the max # of faults allowing FDI is $N$!
- with non-concurrency, e.g., 2 actuator + 2 F/T sensor faults in 2R robot

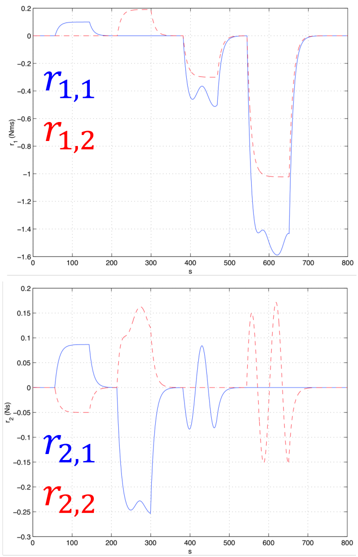
dependence of residuals on considered faults

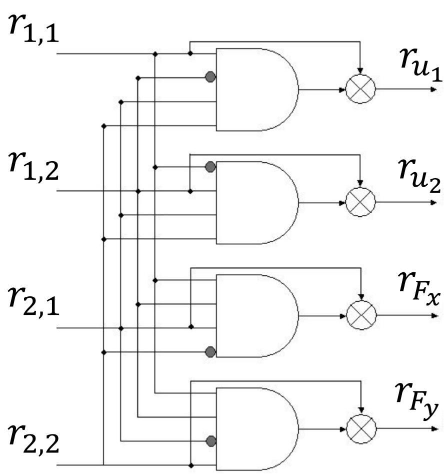
| residual / fault | $r_{1,1}$ | $r_{1,2}$ | $r_{2,1}$ | $r_{2,2}$ |
|---|---|---|---|---|
| $f_{u_1}$ | 1 | 0 | 1 | 1 |
| $f_{u_2}$ | 0 | 1 | 1 | 1 |
| $f_{F_x}$ | 1 | 1 | 1 | 0 |
| $f_{F_y}$ | 1 | 1 | 0 | 1 |

isolation matrix

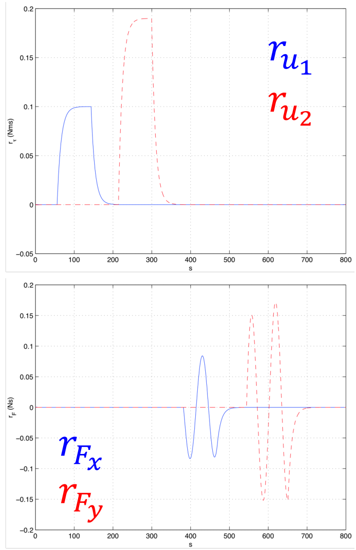
| $r_{2,1}\ r_{2,2}$ / $r_{1,1}\ r_{1,2}$ | 1 1 | 1 0 | 0 1 | 0 0 |
|---|---|---|---|---|
| 1 0 | $f_{u_1}$ | NA | NA | NA |
| 0 1 | $f_{u_2}$ | NA | NA | NA |
| 1 1 | NC | $f_{F_x}$ | $f_{F_y}$ | NA |
| 0 0 | NA | NA | NA | no fault |

time sequence of non-concurrent bias faults: $f_{u_1} \to f_{u_2} \to f_{F_x} \to f_{F_y}$




isolation logics




hybrid residuals allowing **isolation** of 4 faults

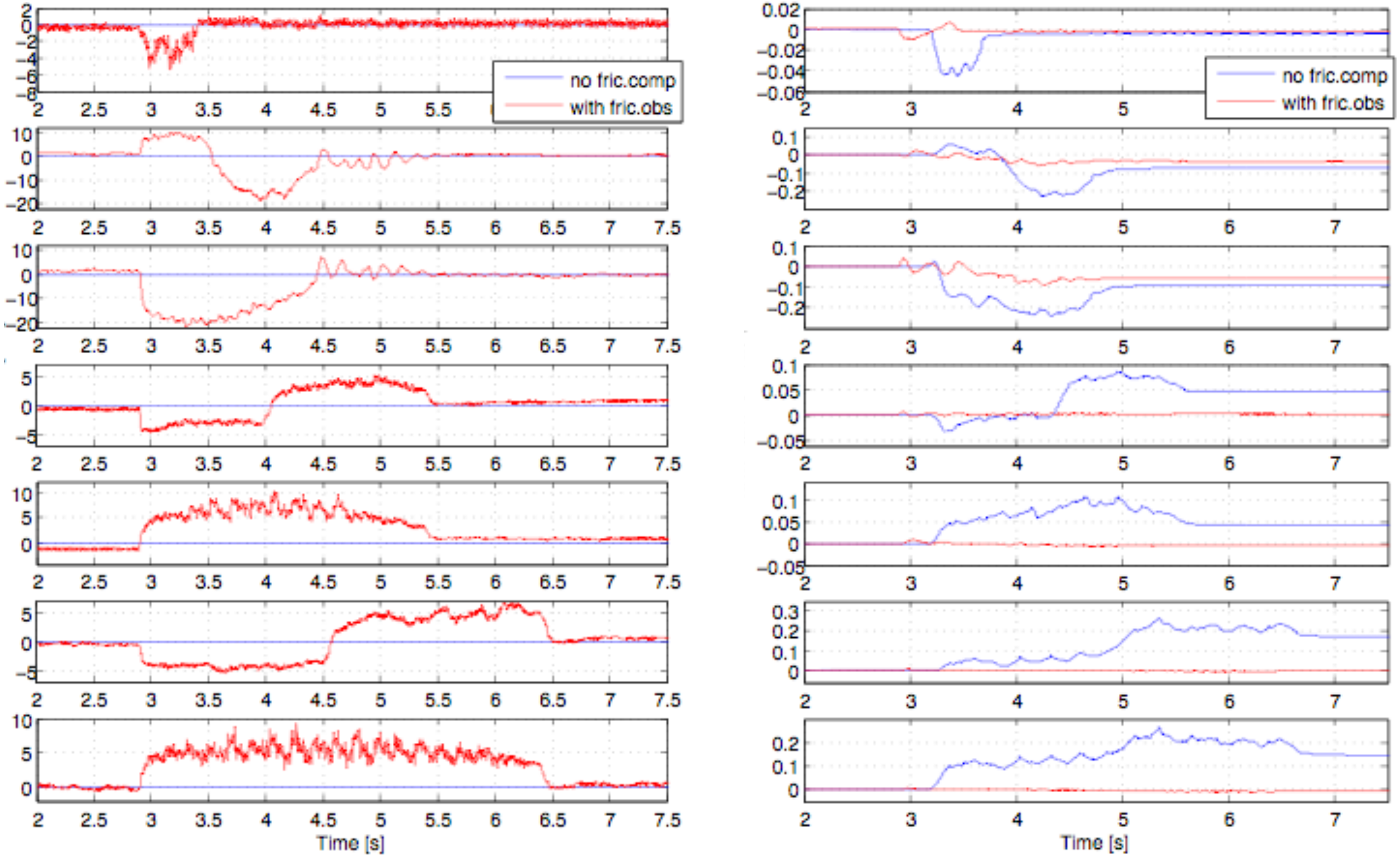
# Experiments on friction compensation

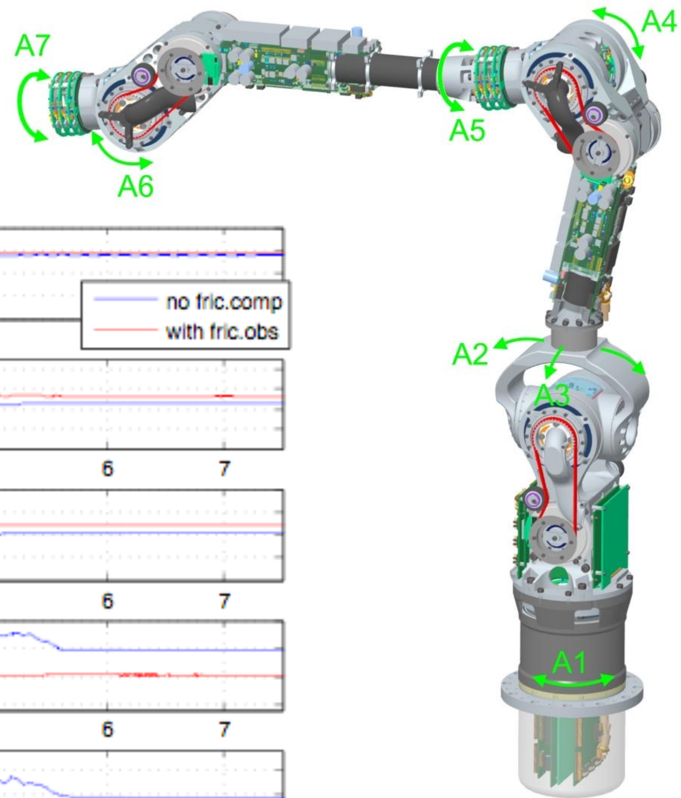
- results on the DLR 7R medical robot

used then on-line in control law...

friction estimate via residuals

position error

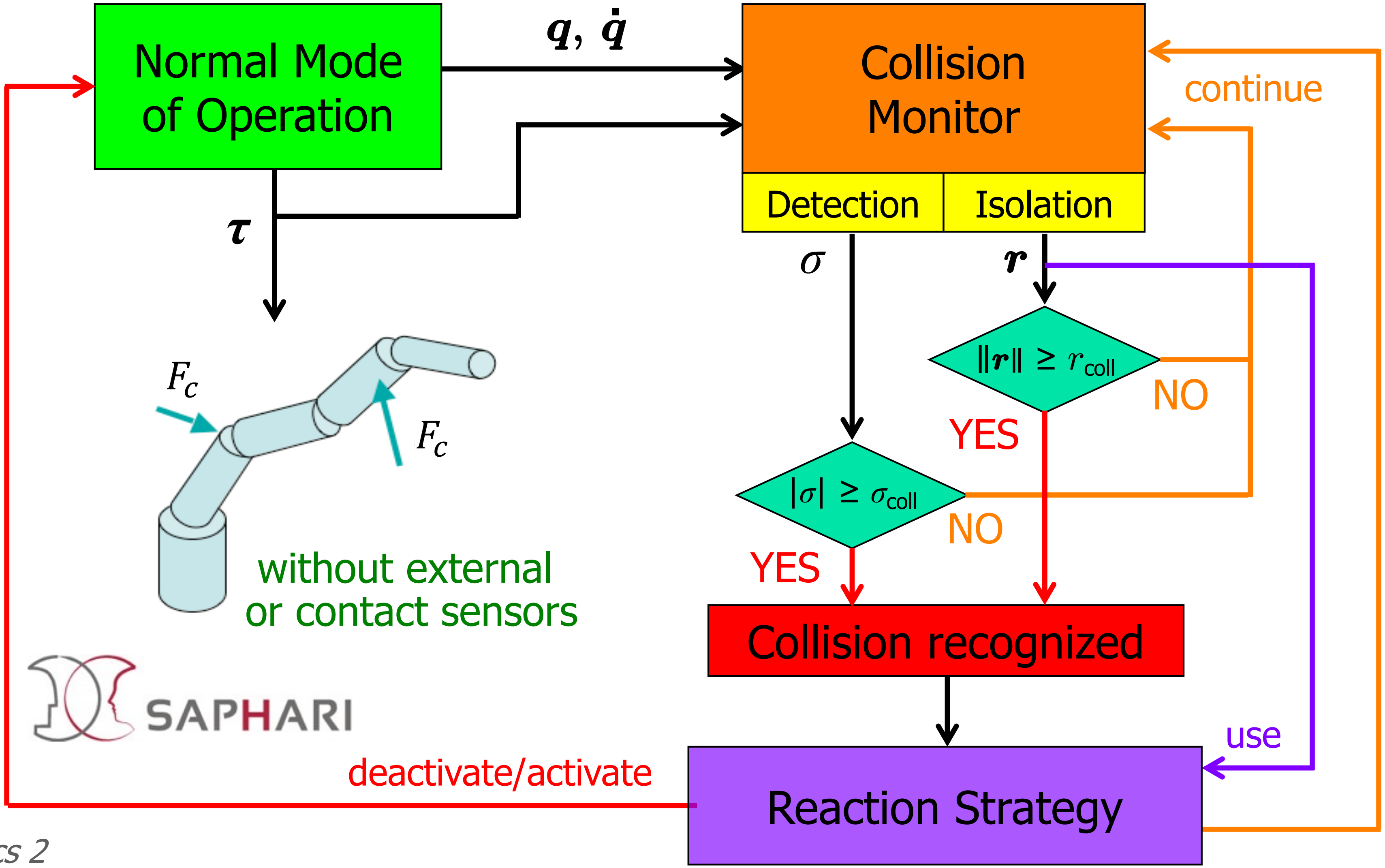



HD at the joints
⇒ elastic joint dynamic model

# Collision detection and isolation
## "sensorless" residuals

$$M(q)\ddot{q} + S(q,\dot{q})\dot{q} + g(q) = \tau + \tau_c \qquad \tau_c = J_c^T(q)F_c$$ (both terms unknown)



# Block diagram of the residual generator

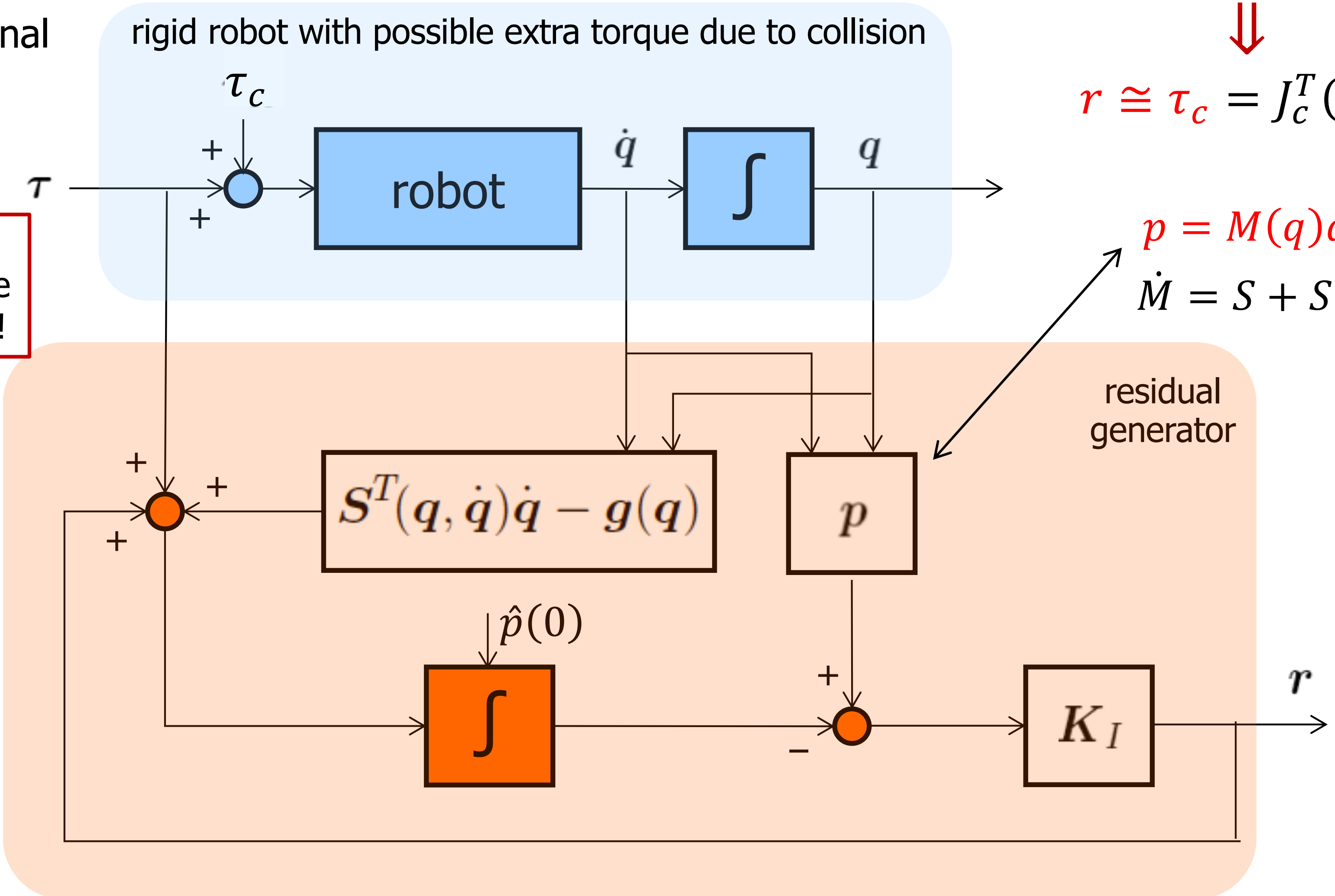
## momentum-based collision detection and isolation

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

$$\Downarrow$$

$$r \cong \tau_c = J_c^T(q)F_c$$

$K_I > 0$, diagonal




$p = M(q)\dot q$

$\dot M = S + S^T$

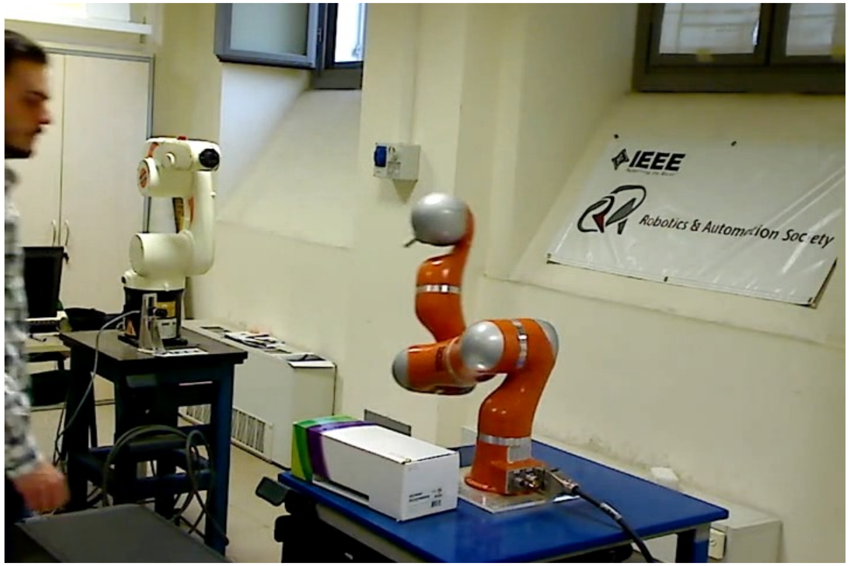
more details in the **pHRI** module on my web page!

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

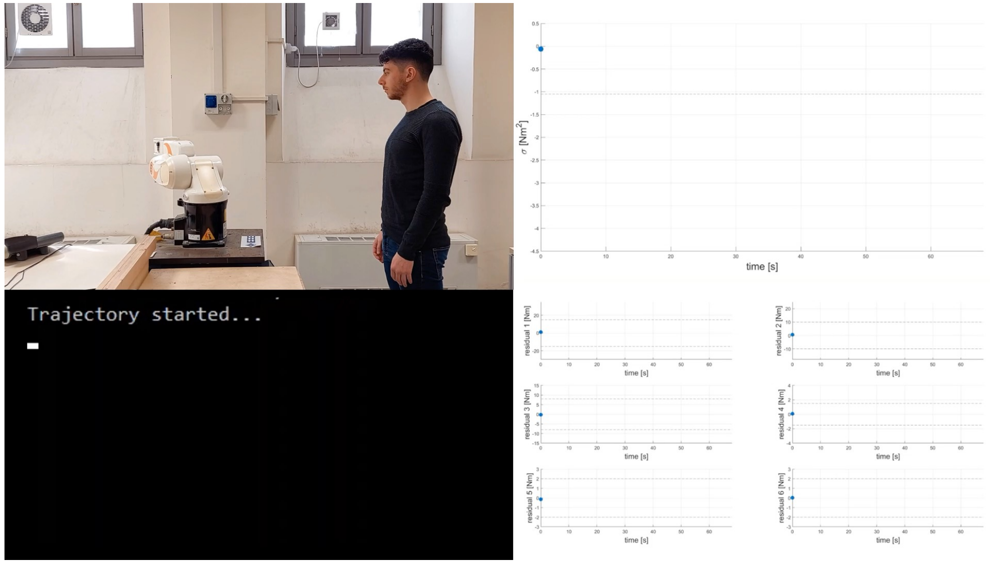
# Collision detection and isolation
## experiments with different robots over the years …

DLR III - **2006**


Neura - **2023**


LWR IV - **2015**



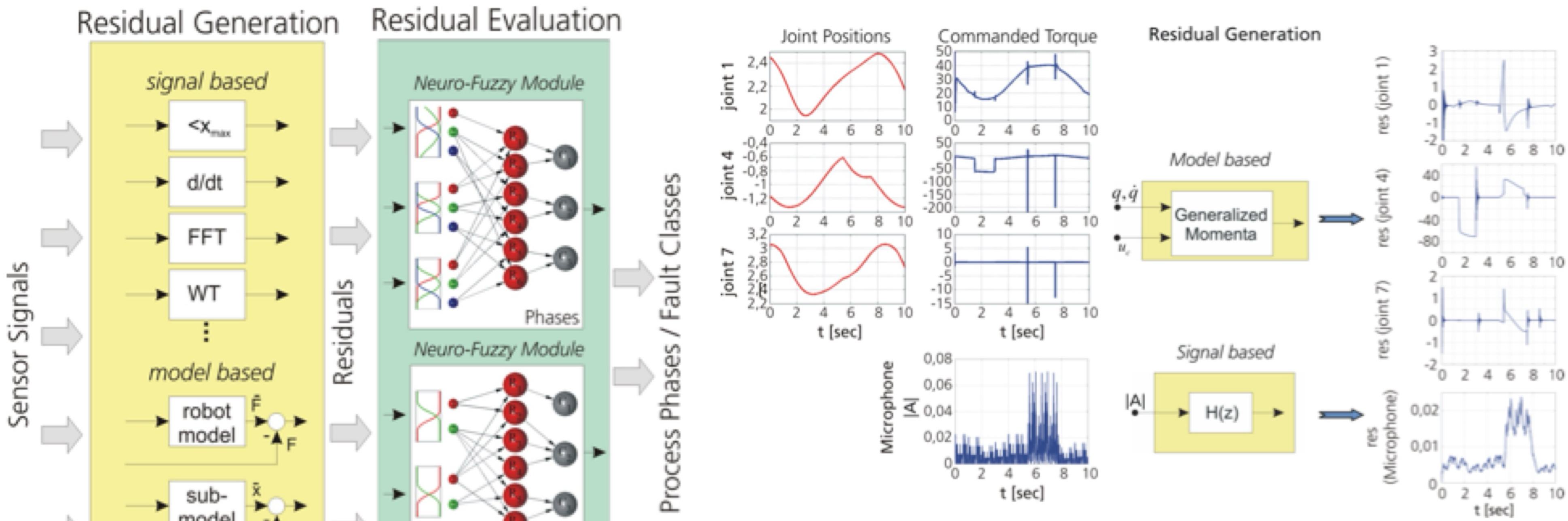

KUKA KR5 – **2022**

4 videos

# Model- and signal-based FDI

- detection and isolation features can be enhanced by combining multiple sensor inputs and different approaches
  - model-based (exact, but require accurate models)
  - signal-based (approximate, but without special requirements)

so as to obtain the "best of both worlds"



# Bibliography


- X. Zhang, M. Polycarpou, T. Parisini, "Robust detection and isolation scheme for abrupt and incipient faults in nonlinear systems," *IEEE Trans. on Automatic Control*, vol. 47, no. 4, pp. 576-592, 2002.
- A. De Luca, R. Mattone, "Actuator failure detection and isolation using generalized momenta," *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 634-639, 2003.
- A. De Luca, R. Mattone, "An adapt-and-detect actuator FDI scheme for robot manipulators," *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 4975-4980, 2004.
- A. De Luca, R. Mattone, "An identification scheme for robot actuator faults," *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp.1127-1131, 2005.
- R. Mattone, A. De Luca, "Relaxed fault detection and isolation: An application to a nonlinear case study," *Automatica*, vol. 42, no. 1, pp. 109-116, 2006.
- R. Mattone, A. De Luca, "Nonlinear fault detection and isolation in a three-tank heating system," *IEEE Trans. on Control Systems Technology*, vol. 14, no. 6, pp. 1158-1166, 2006.
- L. Le Tien, A. Albu-Schäffer, A. De Luca, G. Hirzinger, "Friction observer and compensation for control of robots with joint torque measurements," *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 3789-3795, 2008.
- C. Gaz, A. Cristofaro, A. De Luca, "Detection and isolation of actuator faults and collisions for a flexible robot arm," *Proc. 59th IEEE Conf. on Decision and Control*, pp. 2684-2689, 2020.
- A. De Luca, R. Mattone, "Sensorless robot collision detection and hybrid force/motion control," *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 999-1004, 2005.
- S. Haddadin, A. De Luca, A. Albu-Schäffer, "Robot collisions: A survey on detection, isolation, and identification," *IEEE Transactions on Robotics*, vol. 33, no. 6, pp. 1292-1312, 2017.