*Robotics 2*

# Detection and isolation of robot actuation faults (and collisions)

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# Fault diagnosis problems - 1

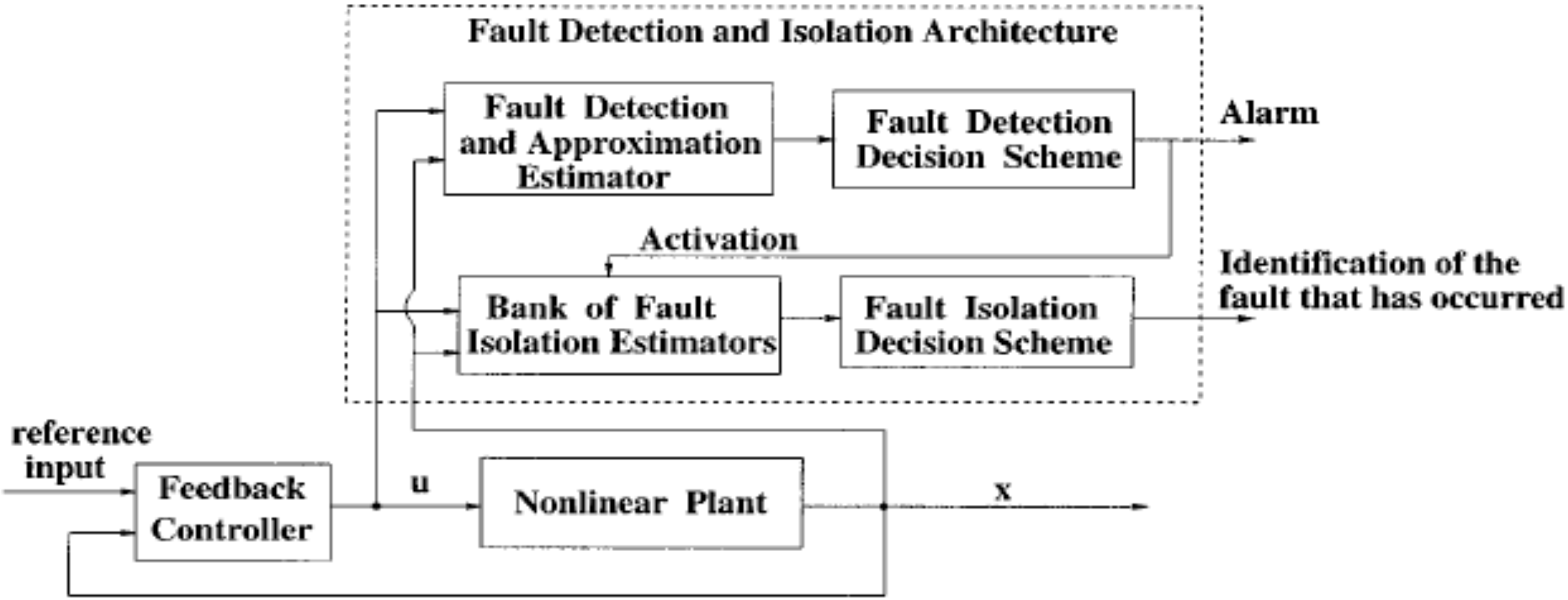
- in the diagnosis of faults possibly affecting a (nonlinear) dynamic system various problems can be formulated
- Fault Detection
  - recognize that the malfunctioning of the (controlled) system is due to the occurrence of a fault (or not proper behavior) affecting some physical or functional component 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)

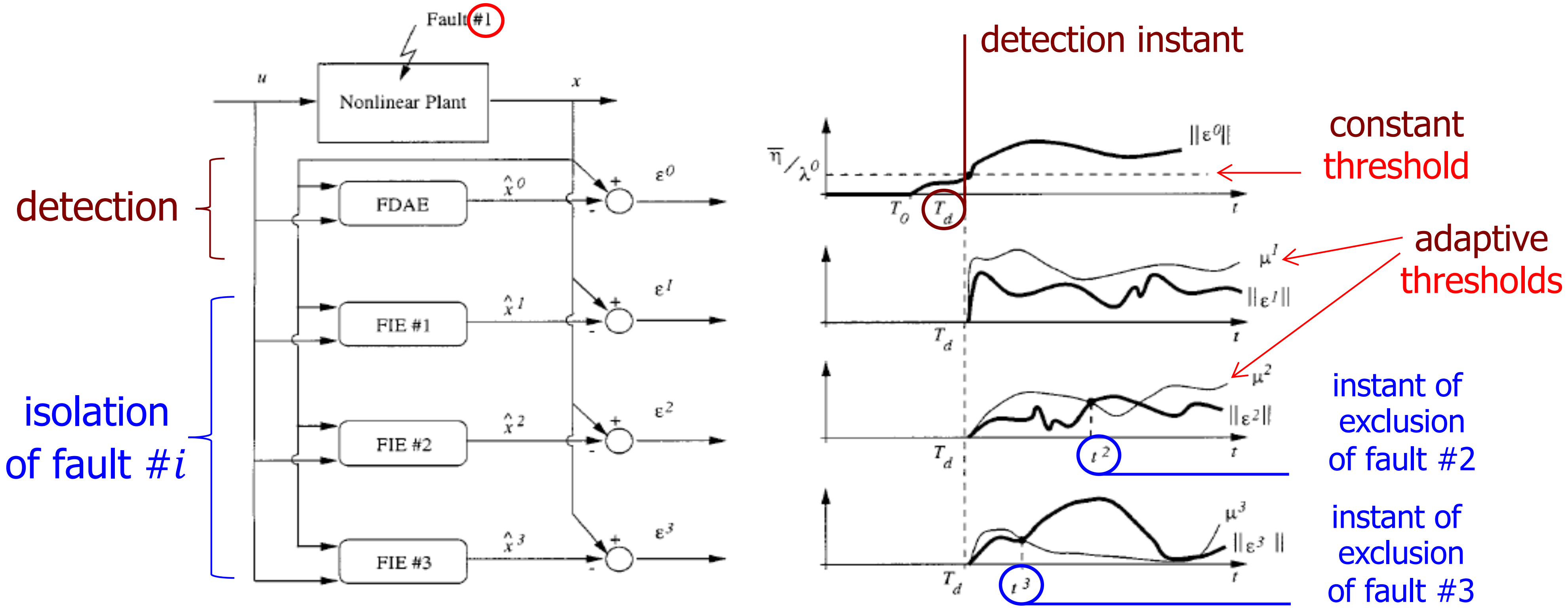
# Typical FDI architecture

- 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 (from the instant $T_0$ of fault start) affect robot reaction
  - avoid false positives (useless alarms) and false negatives (missed events)



# Actuator faults in robots

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

actual torque

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) + B_v\dot{q} + B_c \,\mathrm{sgn}(\dot{q}) = \tau - \tau_f$$

inertia matrix ($> 0$) | centrifugal and Coriolis | gravity | viscous and Coulomb friction | actuation torques

vector of actuation faults (even concurrent on more axes)

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

# Working assumptions

- signals and measurements available
  - the commanded input torque $\tau$, but obviously not $\tau_f$ …
  - 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 $\tau(t)$
  - can be anything (open loop, linear or nonlinear feedback)
- no dependence on/request of a specific motion $q_d(t)$

# Generalized momentum

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

with associated dynamic equation

$$\dot{p} = \tau - \tau_f - \alpha(q, \dot{q})$$

**decoupled** components
relative to the single fault inputs

exploiting structure of centrifugal and Coriolis terms

$$\alpha_i = -\frac{1}{2}\dot{q}^T \frac{\partial M(q)}{\partial q_i}\dot{q} + g_i(q) + B_{vi}\dot{q}_i + B_{ci}\,\mathrm{sgn}(\dot{q}_i)$$

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

# FDI solution

- definition of a vector of residuals

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

$K > 0$
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 $t_i = 1/k_i$

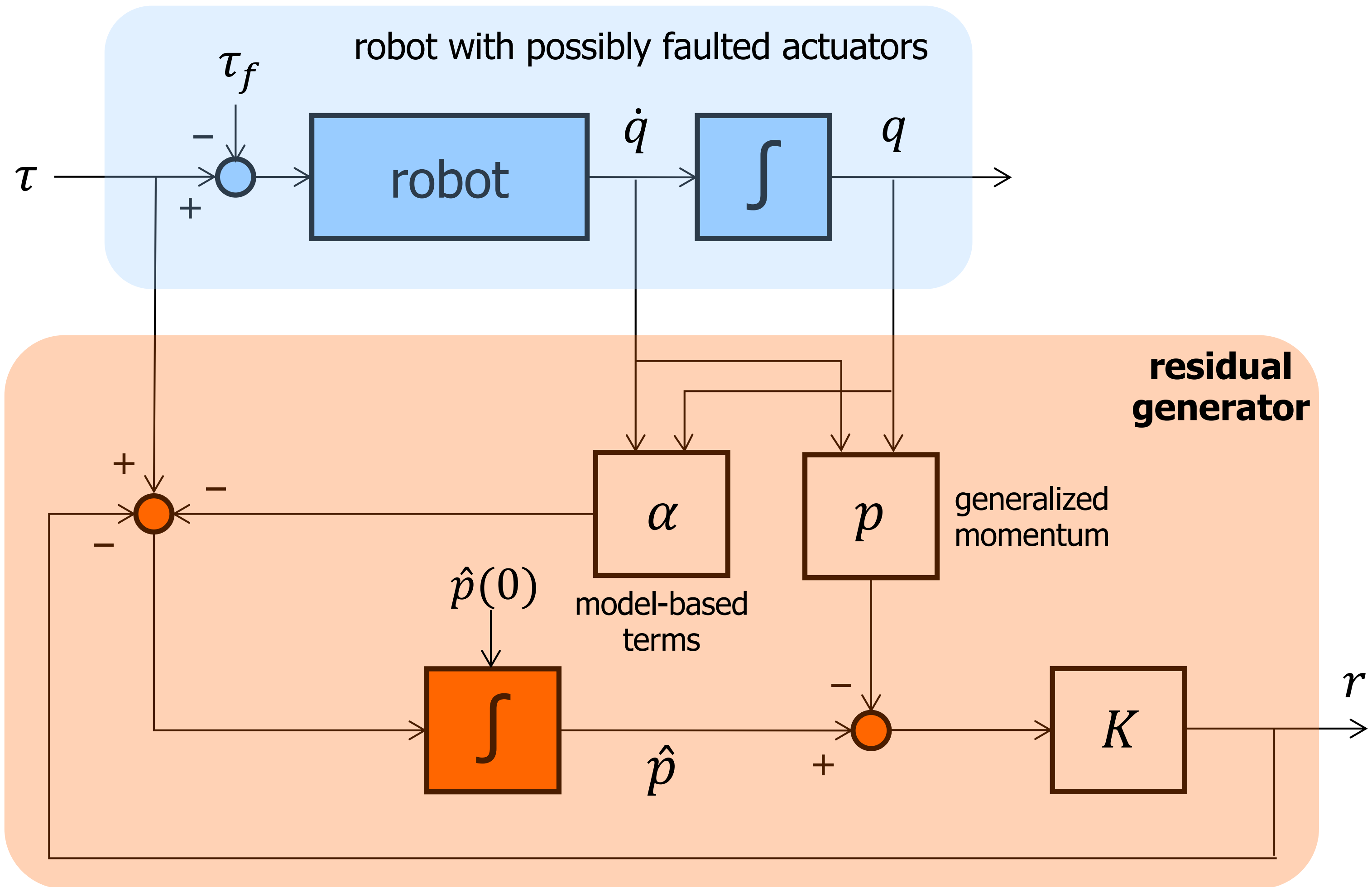
$$\dot{r} = -Kr + K\tau_f$$

in the Laplace domain

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

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

# Block diagram of the residual generator




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

$$r = K\left[\int (\tau - \alpha(q,\dot{q}) - r)dt \; - \; p + p(0)\right] \qquad r(0) = 0$$

# Residual generator as "disturbance observer"

from the block diagram…

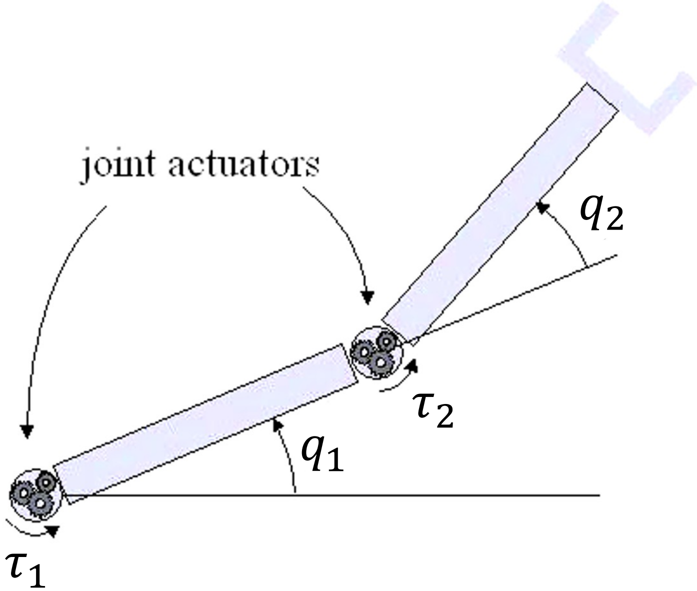
$$\dot{\hat{p}} = \tau - \alpha(q,\dot{q}) + K(p - \hat{p})$$
$$r = K(\hat{p} - p)$$

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

$$e_{obs} = \tau_f - r \quad \Rightarrow \quad \dot{e}_{obs} = \dot{\tau}_f - \dot{r} = \dot{\tau}_f - K(\dot{\hat{p}} - \dot{p})$$
$$= \dot{\tau}_f - K\Big((\tau - \alpha - r) - (\tau - \alpha - \tau_f)\Big)$$
$$= \dot{\tau}_f - K(\tau_f - r) = \dot{\tau}_f - K e_{obs} \cong -K e_{obs}$$

# A worked-out example

- planar 2R robot under gravity




dynamic model (without friction)

$$M(q)\ddot{q} + \underbrace{c(q,\dot{q})}_{= C(q,\dot{q})\dot{q}} + g(q) = \tau - \tau_f$$

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

$$+ \begin{pmatrix} a_4c_1 + a_5c_{12} \\ a_5c_{12} \end{pmatrix} = \begin{pmatrix} \tau_1 - \tau_{f,1} \\ \tau_2 - \tau_{f,2} \end{pmatrix}$$

computation of the residual vector

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

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

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

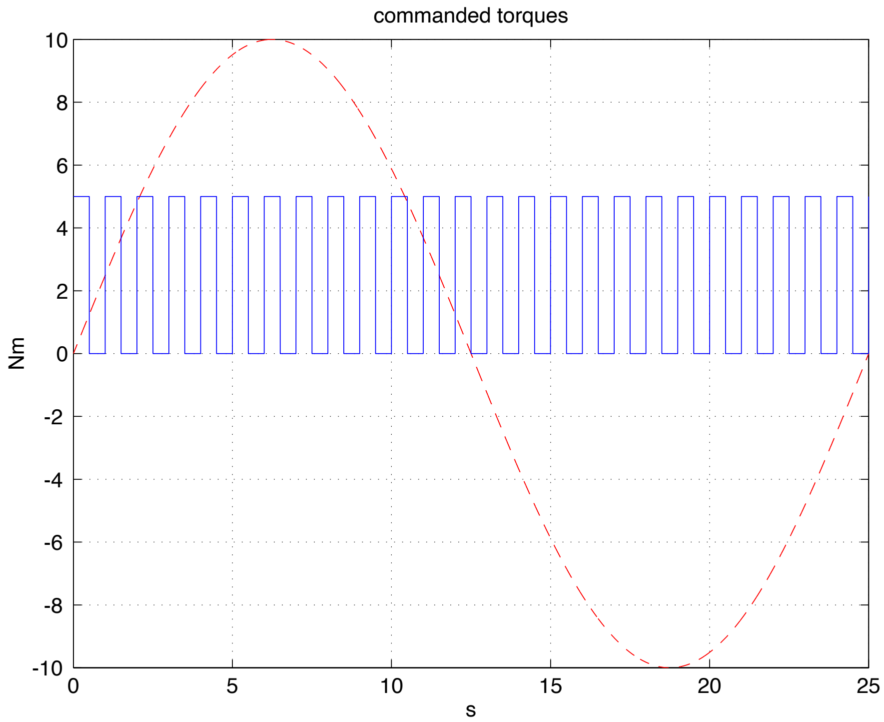
$$\alpha_2 = -\frac{1}{2}\dot{q}^T\frac{\partial M(q)}{\partial q_2}\dot{q} + g_2(q)$$

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

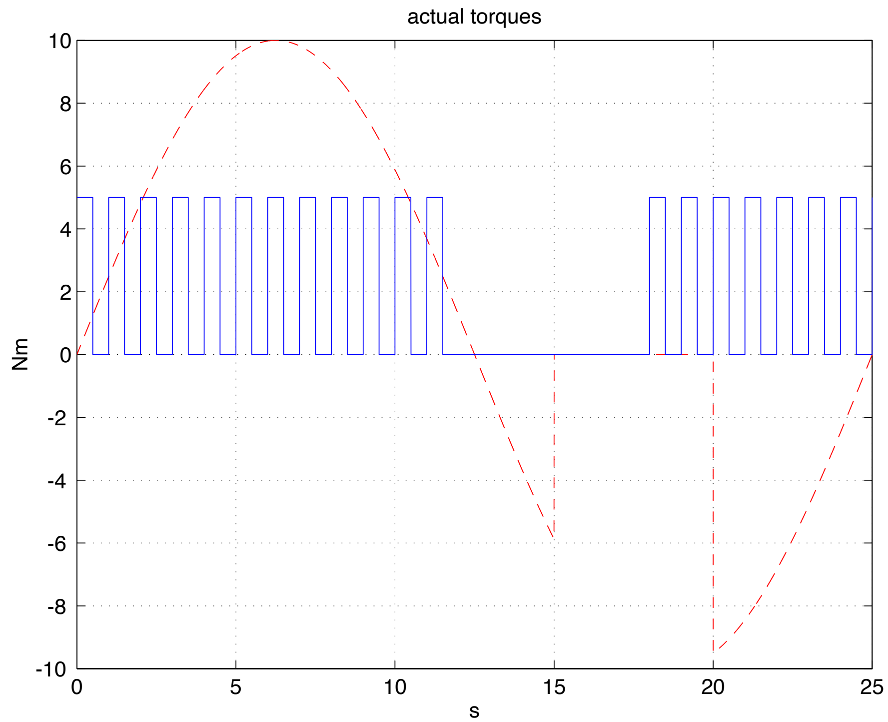
# Faults on both actuators

## (total, intermittent, concurrent)

**commanded torques (in open loop)**




**actual (faulted) torques**



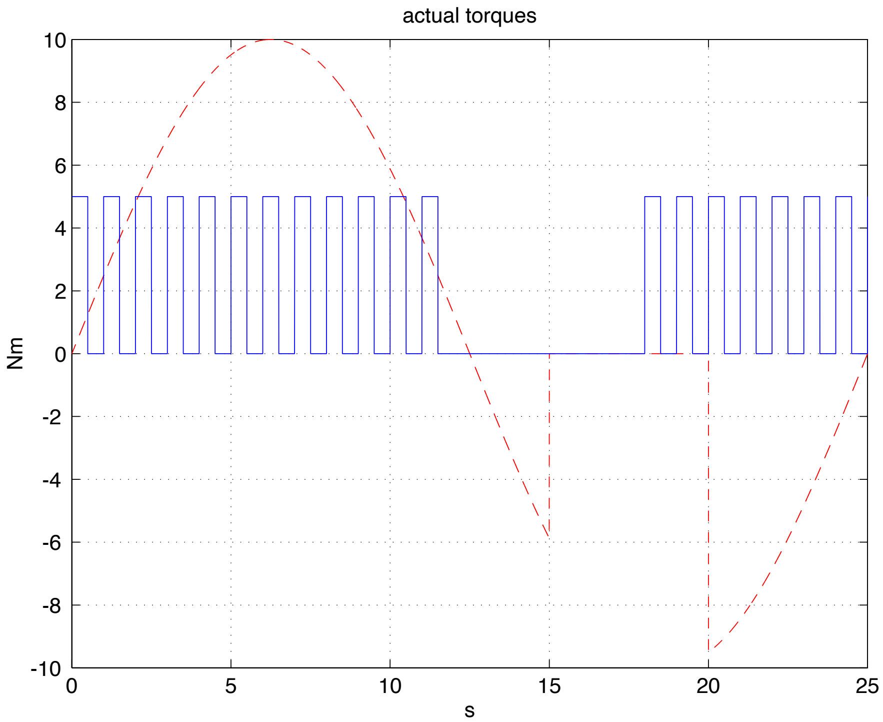

= first joint (fault for $t \in [15 \div 20]$ sec)

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

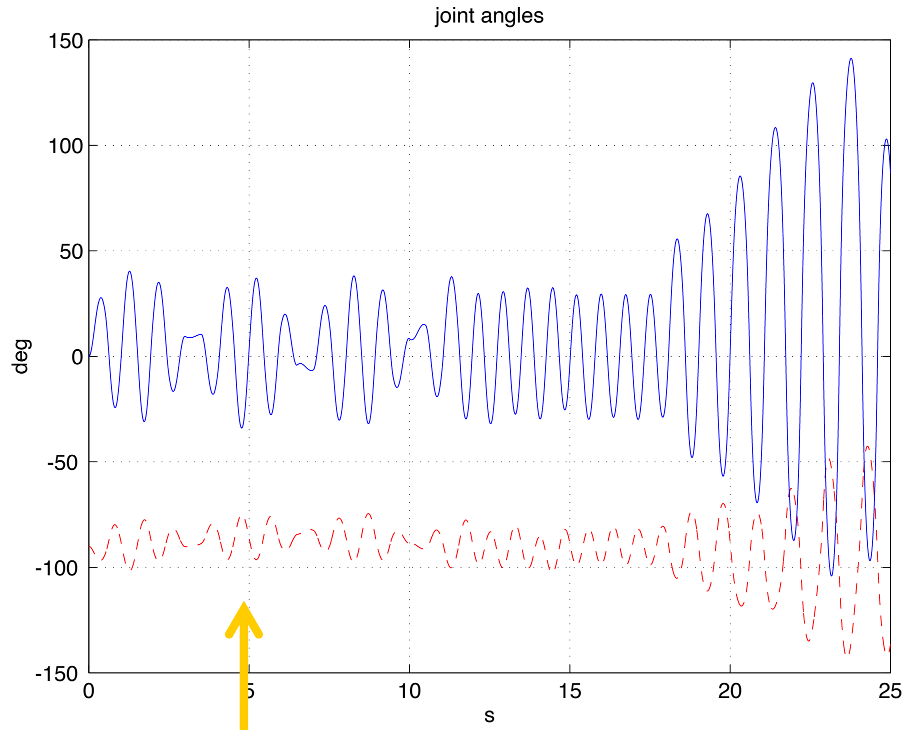
time interval of fault concurrence $t \in [15 \div 18]$ sec

# First simulation

actual torques (to the robot)




(measured) joint positions



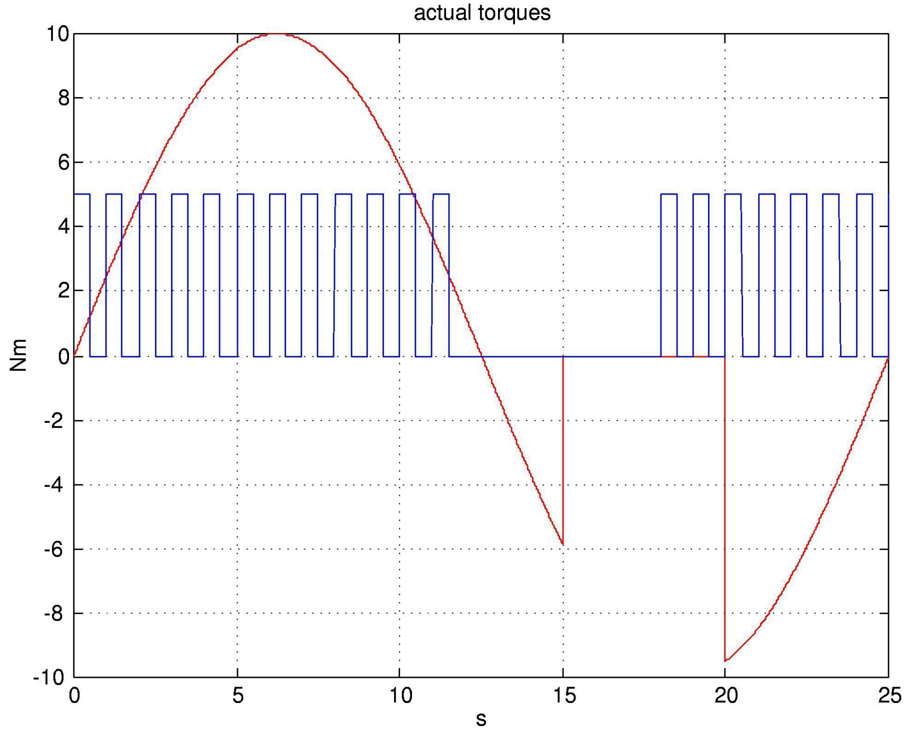

= first joint

= second joint

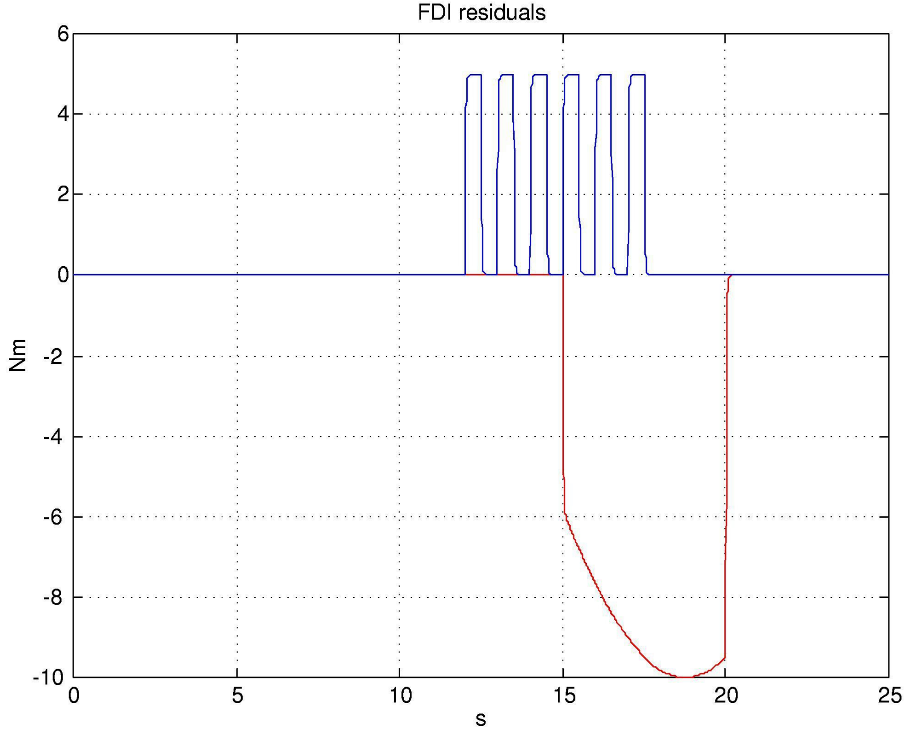
no clear evidence of faults in the dynamic evolution of the system!

# First simulation – FDI

actual torques (to the robot)




residuals




= first joint

= second joint

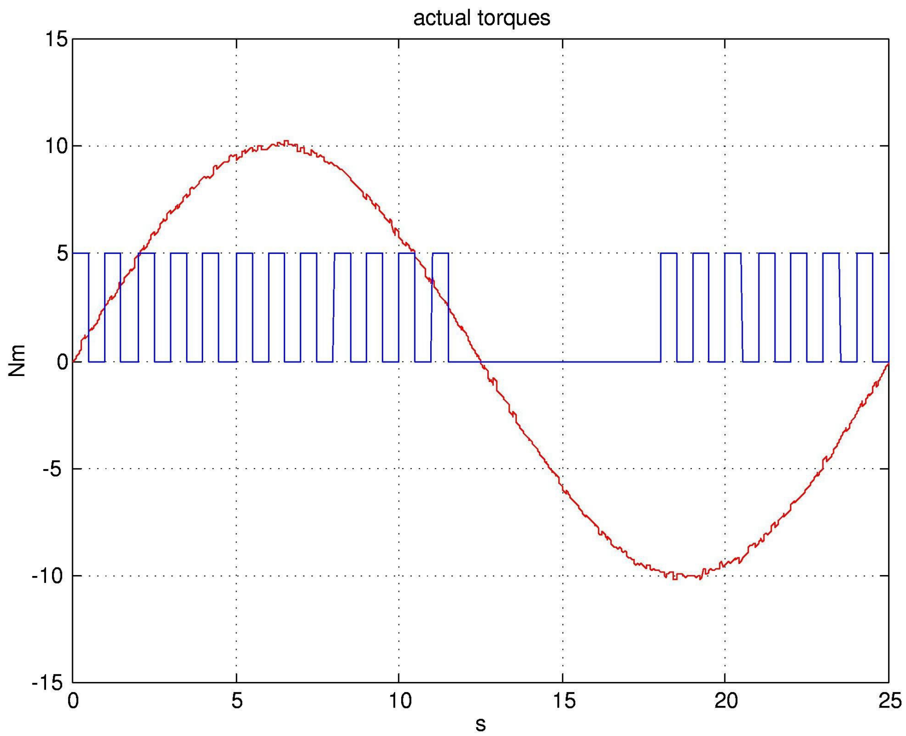
$$K = \mathrm{diag}\{50, 50\}$$

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

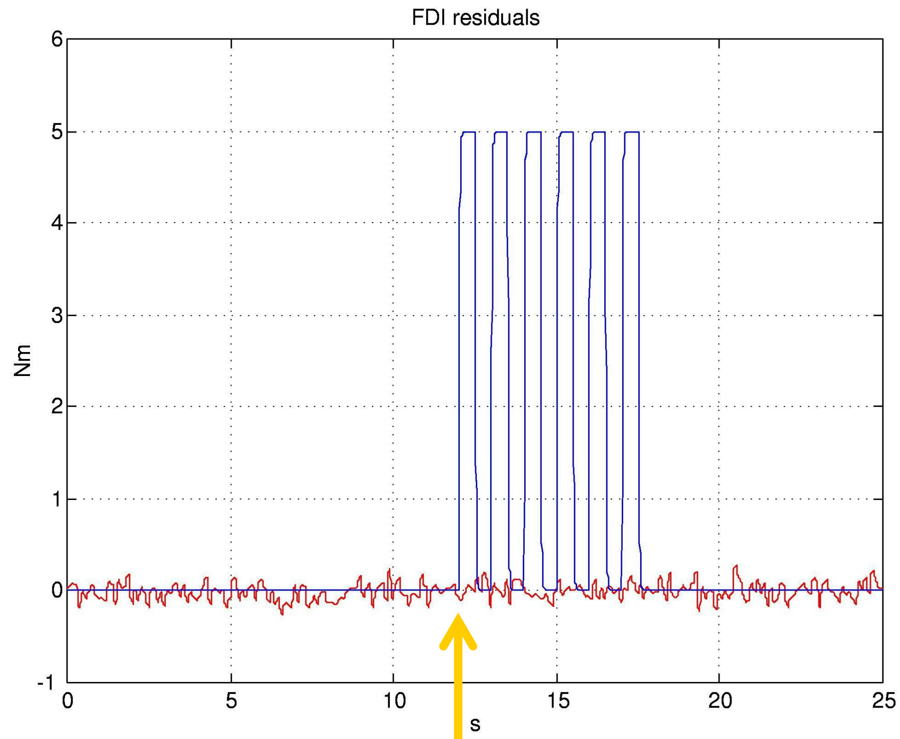
# Second simulation – FDI

## (total fault on second actuator, added noise on first channel)

**actual torques (to the robot)**




**residuals**




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

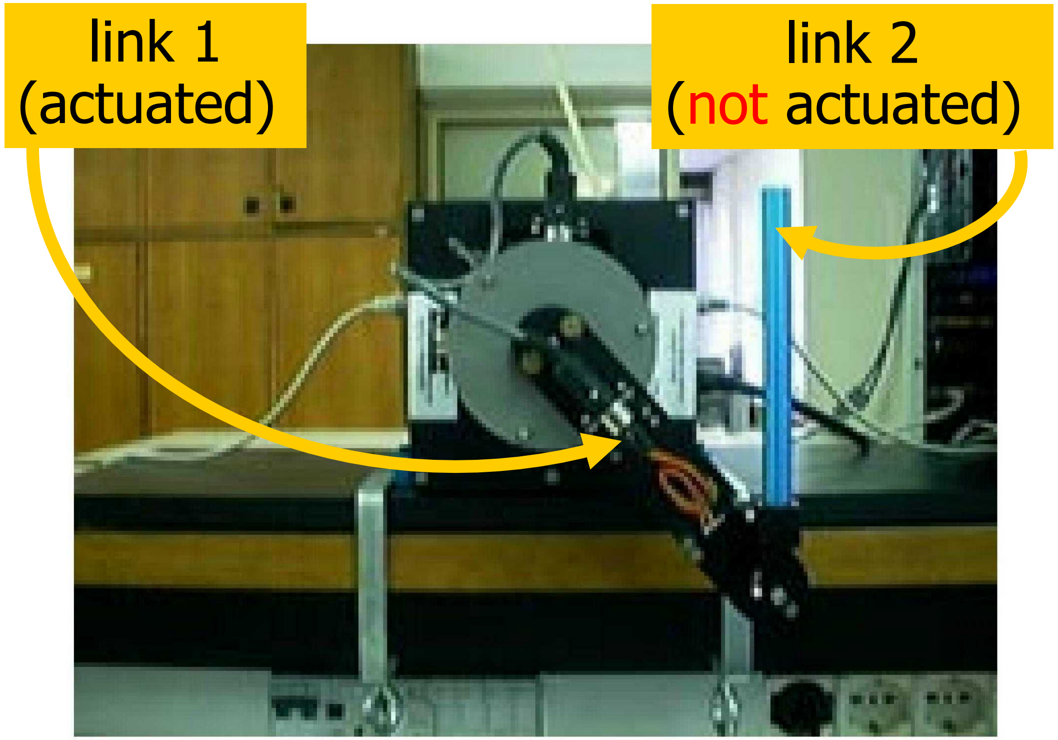
red line = first joint

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

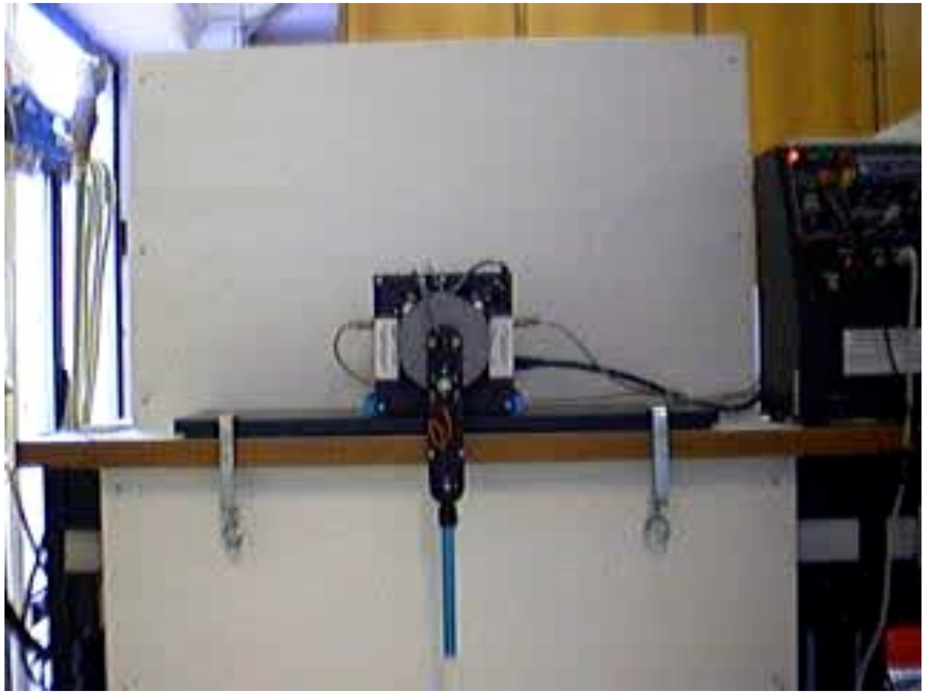
# Experimental setup

## Quanser Pendubot

video




with encoders on both joints



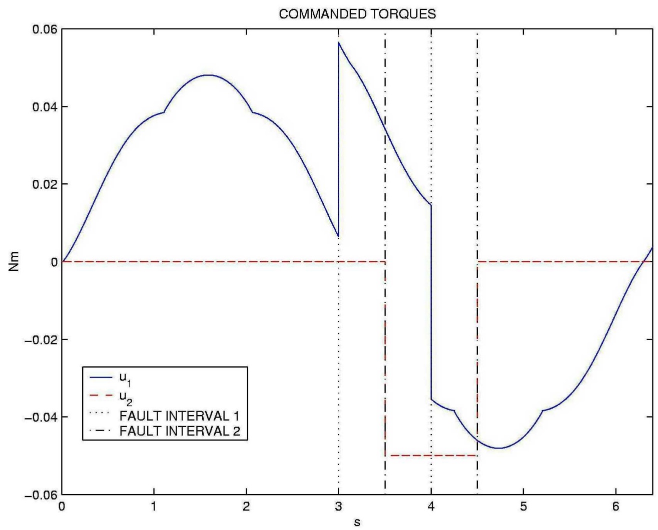
nonlinear control for swing-up

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

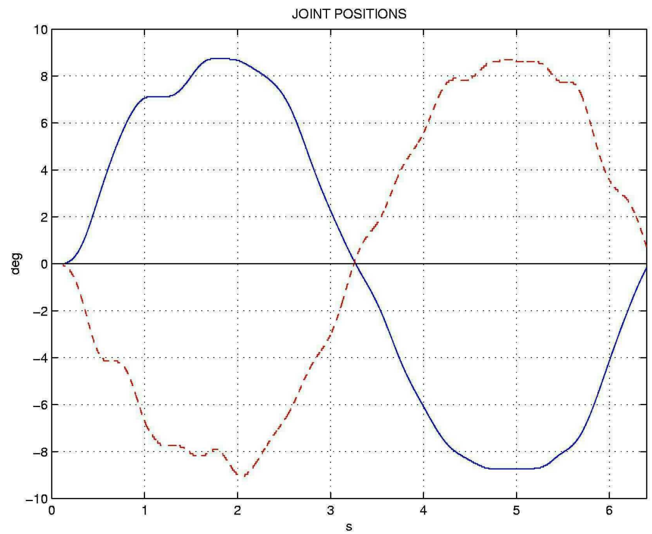
# First experiment

- motor 1 driven by sinusoidal voltage of period 2π sec (open loop)
- bias fault on $\tau_1$ 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 available at the joint to provide 0.05 Nm …)
- fault concurrency for $t \in [3.5 \div 4]$ sec

commanded torques



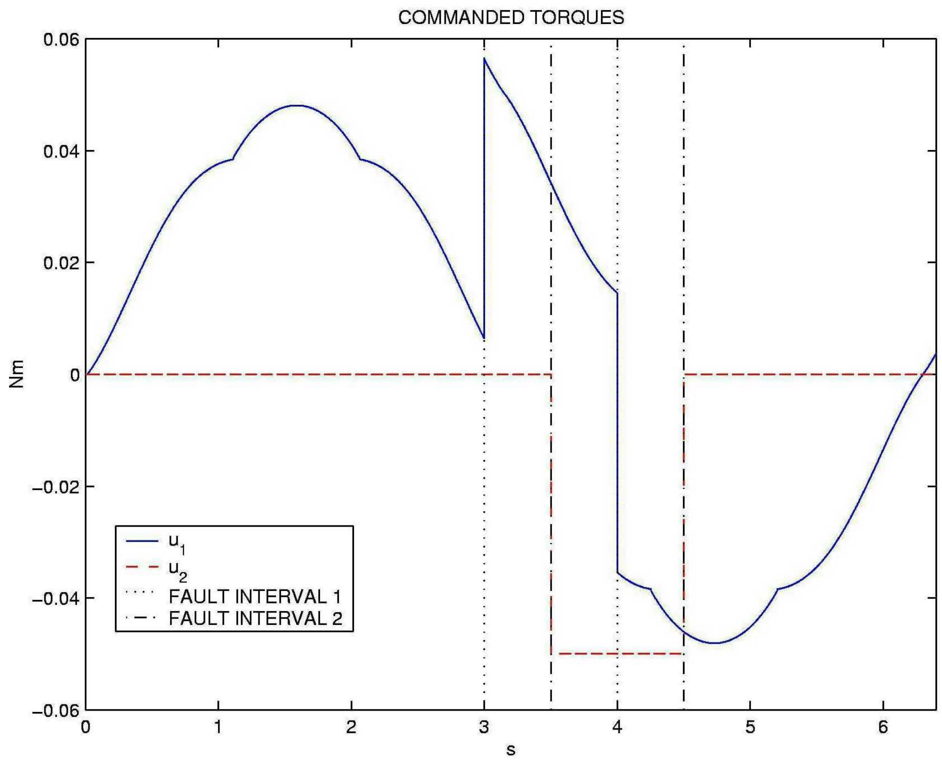

joint positions



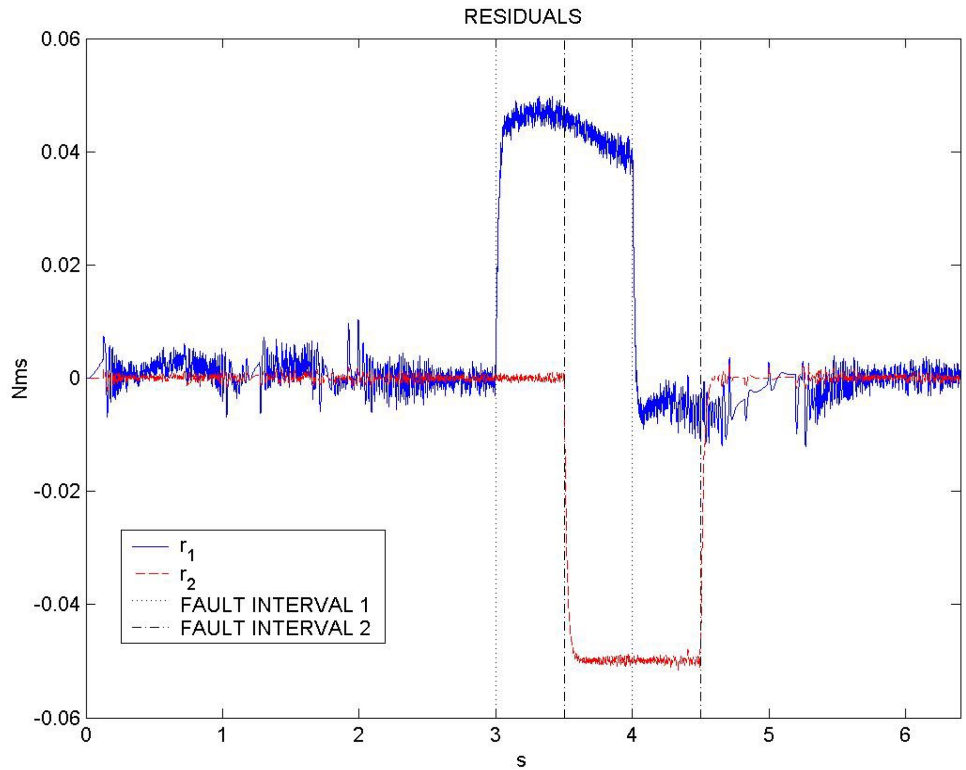

joint 1 — joint 2

# First experiment – FDI

commanded torques




residuals

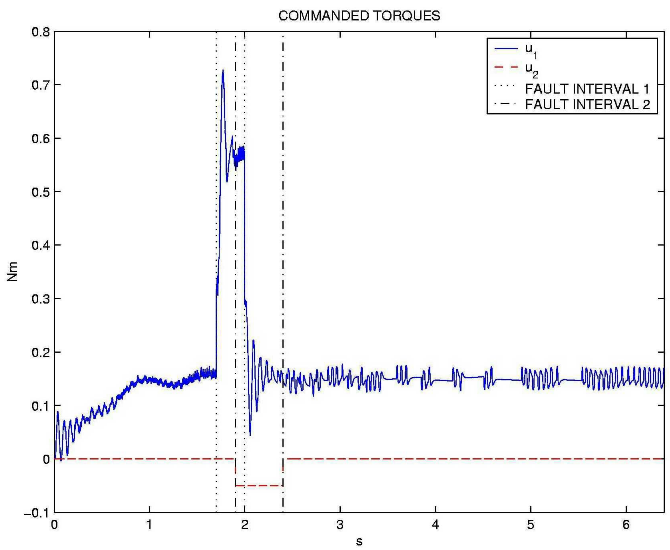



joint 1 — joint 2

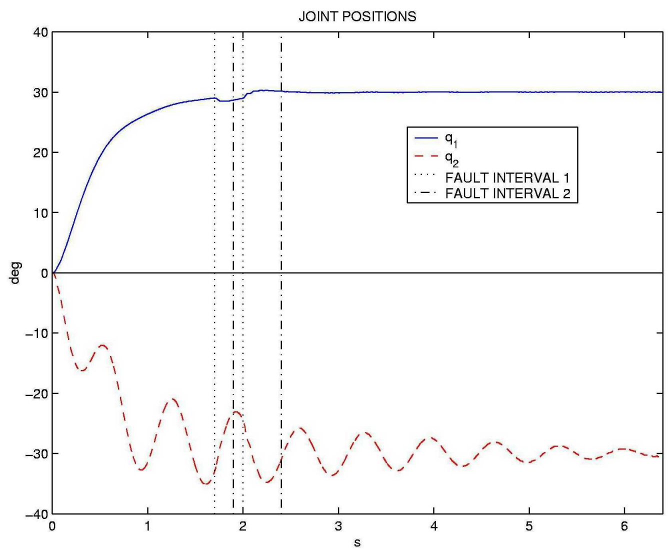
# Second experiment

- position regulation of the first joint at $q_{d1} = 30°$ (under 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 $t \in [1.9 \div 2]$ sec

commanded torques



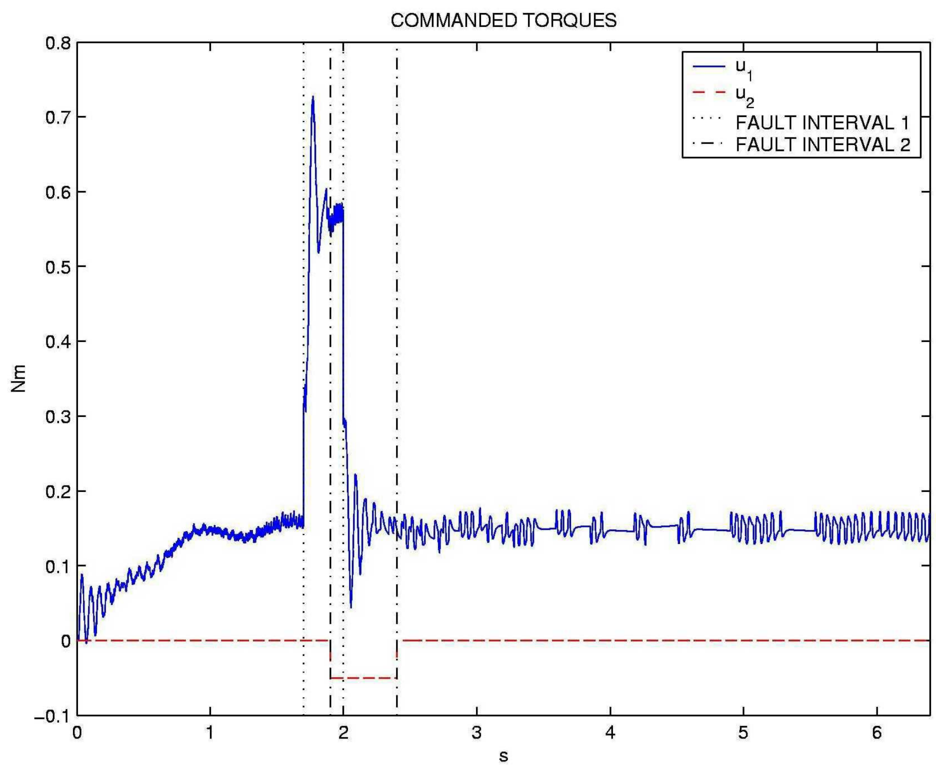

joint positions



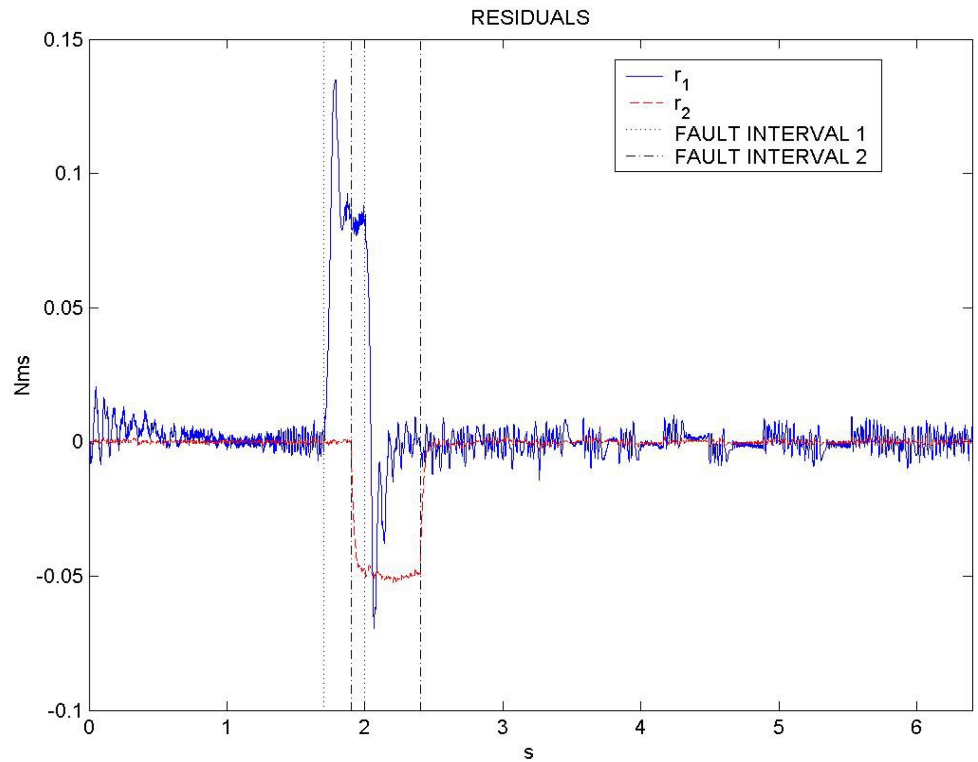

joint 1 — joint 2 - - -

# Second experiment – FDI

commanded torques




residuals




joint 1 joint 2

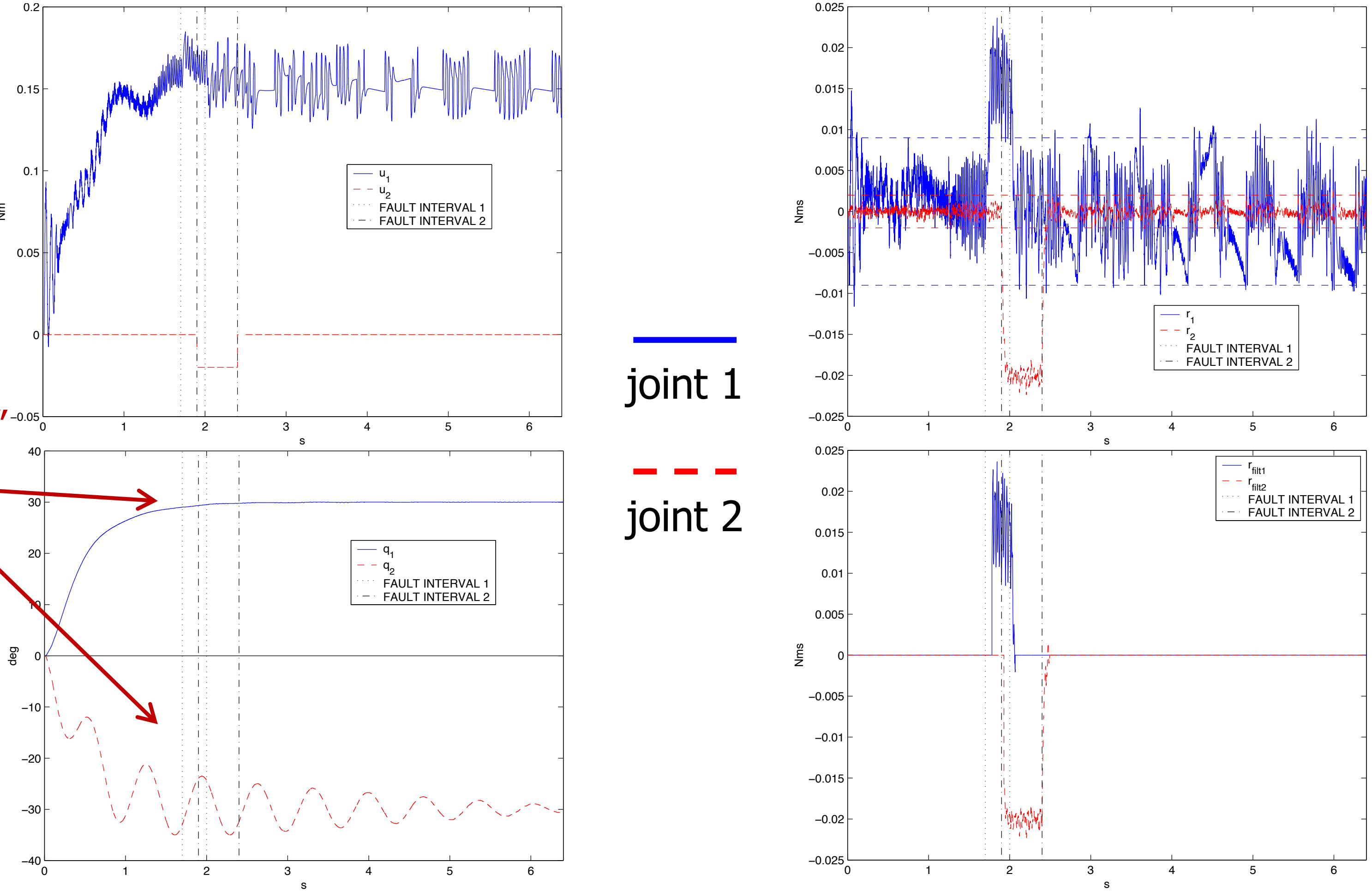
# Third experiment – FDI

- 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 seem "unobservable" in these evolutions

joint positions




residuals

filtered residuals

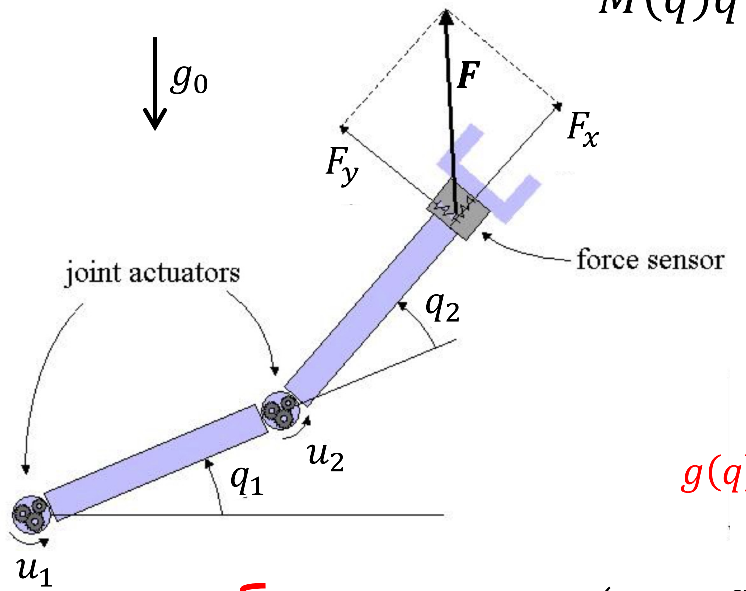
# Some extensions

- 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 (though possibly needing the use of acceleration) to handle parametric uncertainties in 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
- 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)
- extended to robot collision detection and isolation (for safe HRI!)
- 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

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




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

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 $J^{ad} = \det(J) \cdot J^{-1}$
⇒ a singularity robust scheme!

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

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

$$\dot{\zeta} = -(J^T)^{ad}(q)\begin{pmatrix} a_4 c_1 + a_5 c_{12} \\ a_5 c_{12} + a_2 s_2 \dot{q}_1(\dot{q}_1 + \dot{q}_2) \end{pmatrix} + \begin{pmatrix} 0 & \ell_1 s_2 \dot{q}_2 \\ 0 & \ell_1 c_2 \dot{q}_2 \end{pmatrix} M(q)\dot{q} + (J^T)^{ad}(q)\tau$$

$$+ \ell_1 \ell_2 s_2 F_m + K[(J^T)^{ad}(q)M(q)\dot{q} - \zeta]$$

$$r = (J^T)^{ad}(q)M(q)\dot{q} - \zeta$$

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

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

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

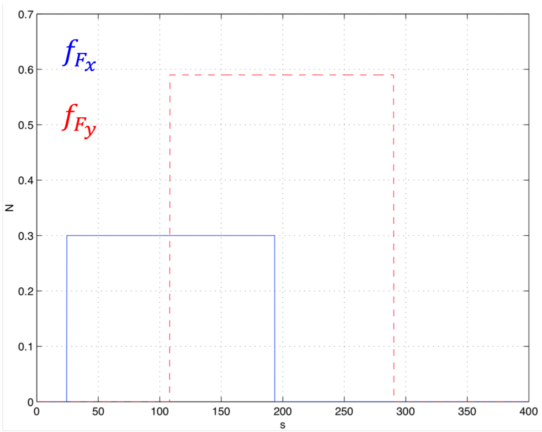
decoupled, though modulated by $q_2$

homework: prove this expression

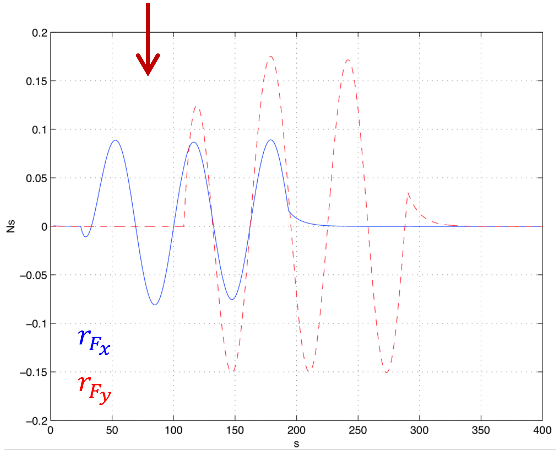
# Isolation of F/T sensor faults

- simulation on the 2R robot

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



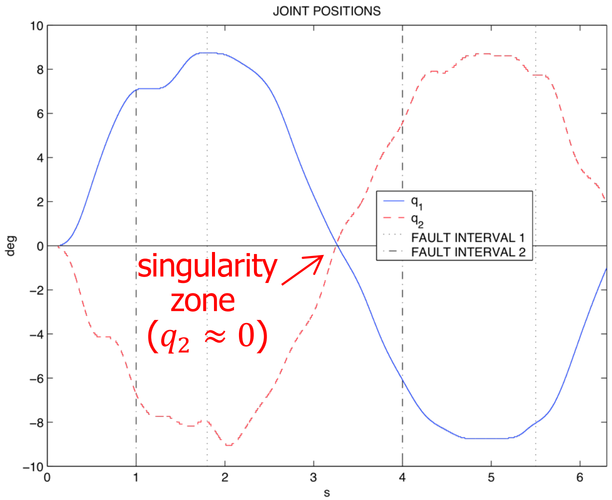

$q_2$ is tracking a sinusoid ($A = \pi/8$ rad, $\omega = 0.1$ rad/s)

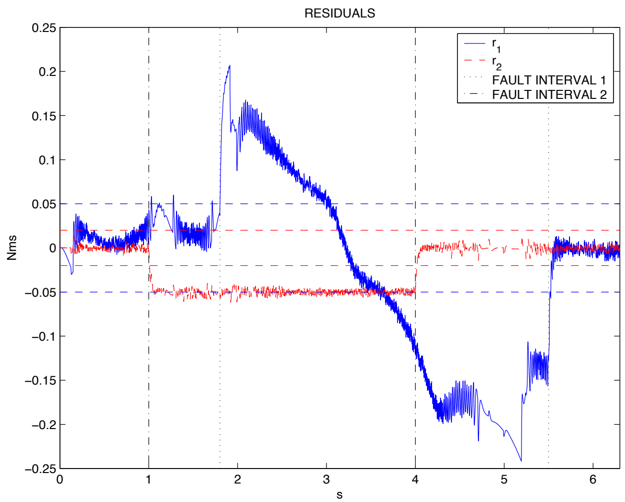



FDI residual components (with $K = 0.1I$)

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

evolution of joint variables




residuals response to emulated bias faults on force measures
-1 N on $F_x$ in $t \in [1.8 \div 5.5]$
0.05 N 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 actuators AND faults of 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

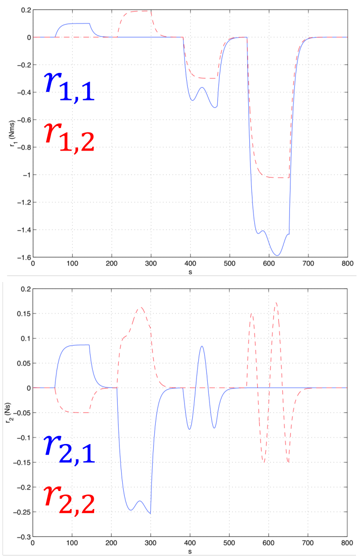
dependence of residuals on considered faults

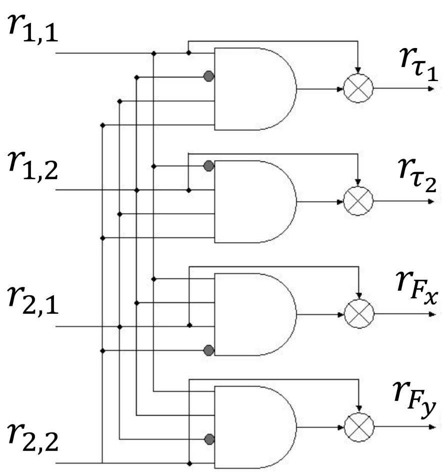
| fault \ residual | $r_{1,1}$ | $r_{1,2}$ | $r_{2,1}$ | $r_{2,2}$ |
|---|---|---|---|---|
| $f_{\tau_1}$ | 1 | 0 | 1 | 1 |
| $f_{\tau_2}$ | 0 | 1 | 1 | 1 |
| $f_{F_x}$ | 1 | 1 | 1 | 0 |
| $f_{F_y}$ | 1 | 1 | 0 | 1 |

isolation matrix

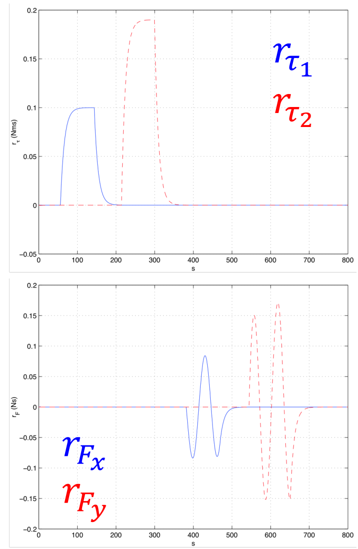
| $r_{1,1}\ r_{1,2}$ \ $r_{2,1}\ r_{2,2}$ | 1 1 | 1 0 | 0 1 | 0 0 |
|---|---|---|---|---|
| 1 0 | $f_{\tau_1}$ | NA | NA | NA |
| 0 1 | $f_{\tau_2}$ | NA | NA | NA |
| 1 1 | NC | $f_{F_x}$ | $f_{F_y}$ | NA |
| 0 0 | NA | NA | NA | no fault |

time sequence of non-concurrent bias faults: $f_{\tau_1} \rightarrow f_{\tau_2} \rightarrow f_{F_x} \rightarrow f_{F_y}$




isolation logics



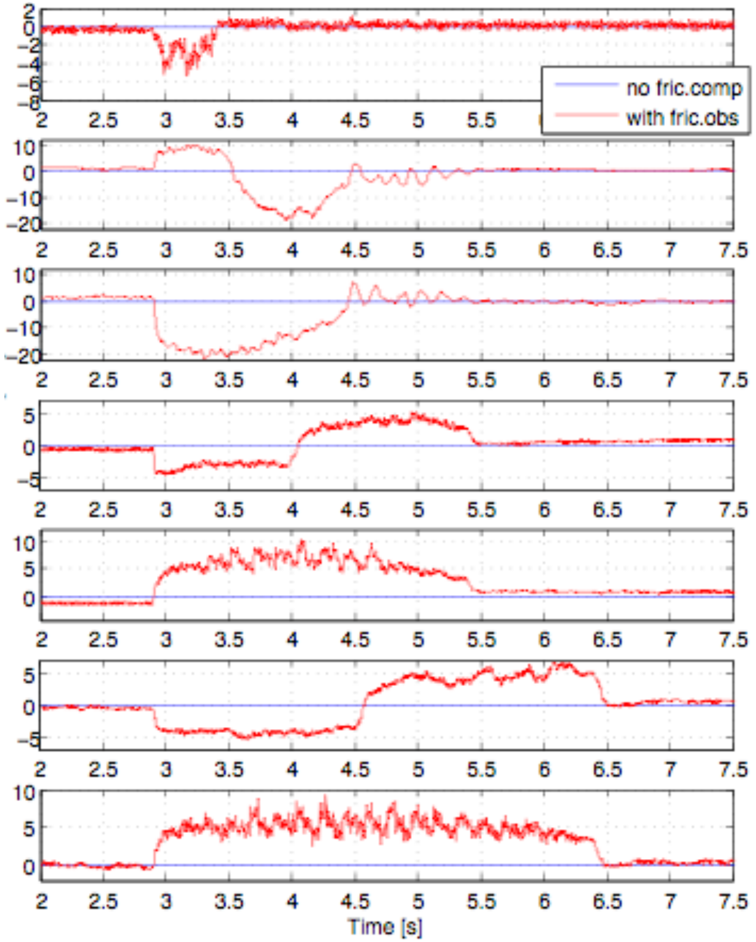

hybrid residuals (in continuous time + digital logics) allow **isolation** of 4 faults in this case

# Experiments on friction compensation

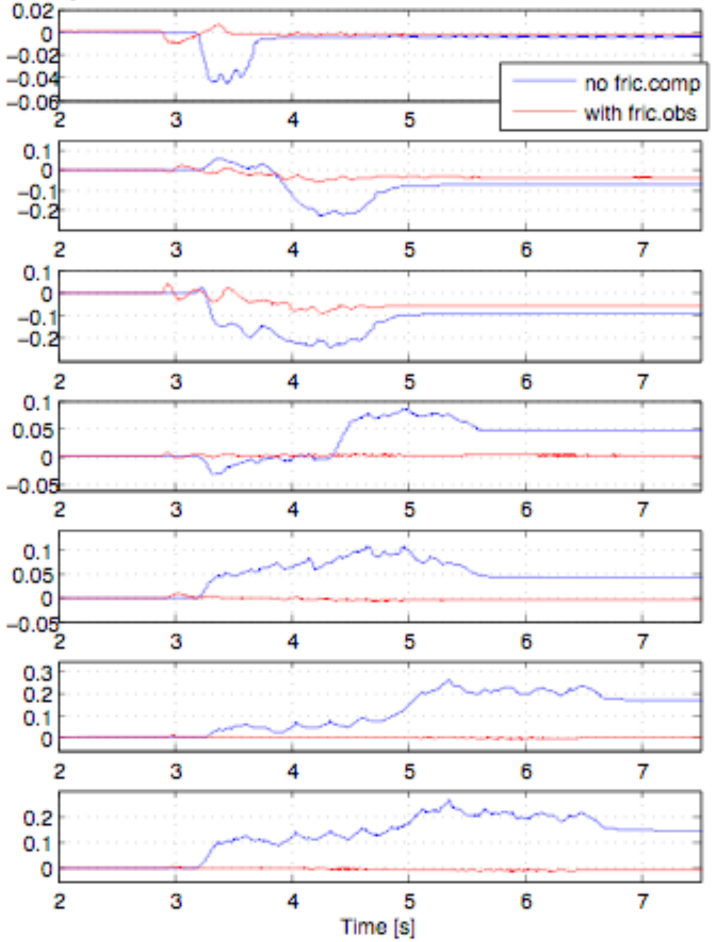
- results on DLR 7R medical robot

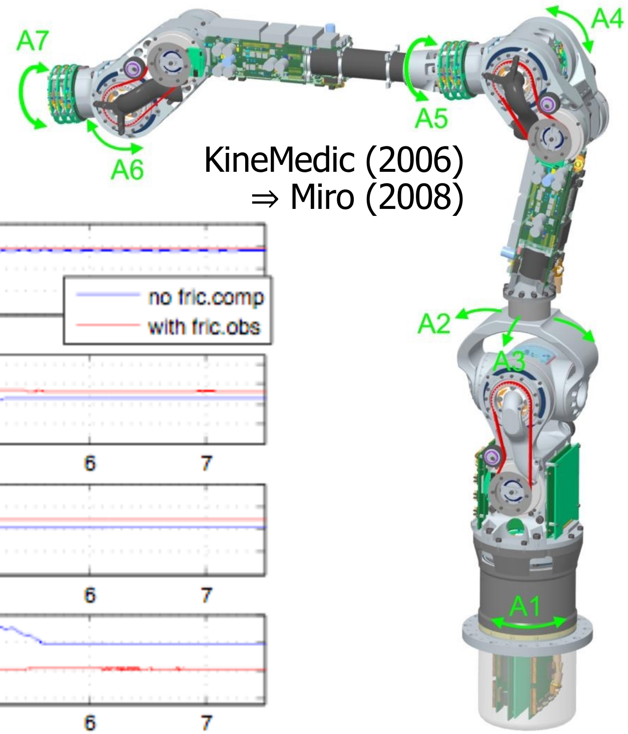
used then online in control law ...

friction estimate via residuals




position error




KineMedic (2006)
⇒ Miro (2008)

HD at the joints
⇒ elastic joint dynamic model

$$M_m\ddot{\theta} + \tau_J = \tau - \tau_B$$

$$\tau_J = K(\theta - q)$$

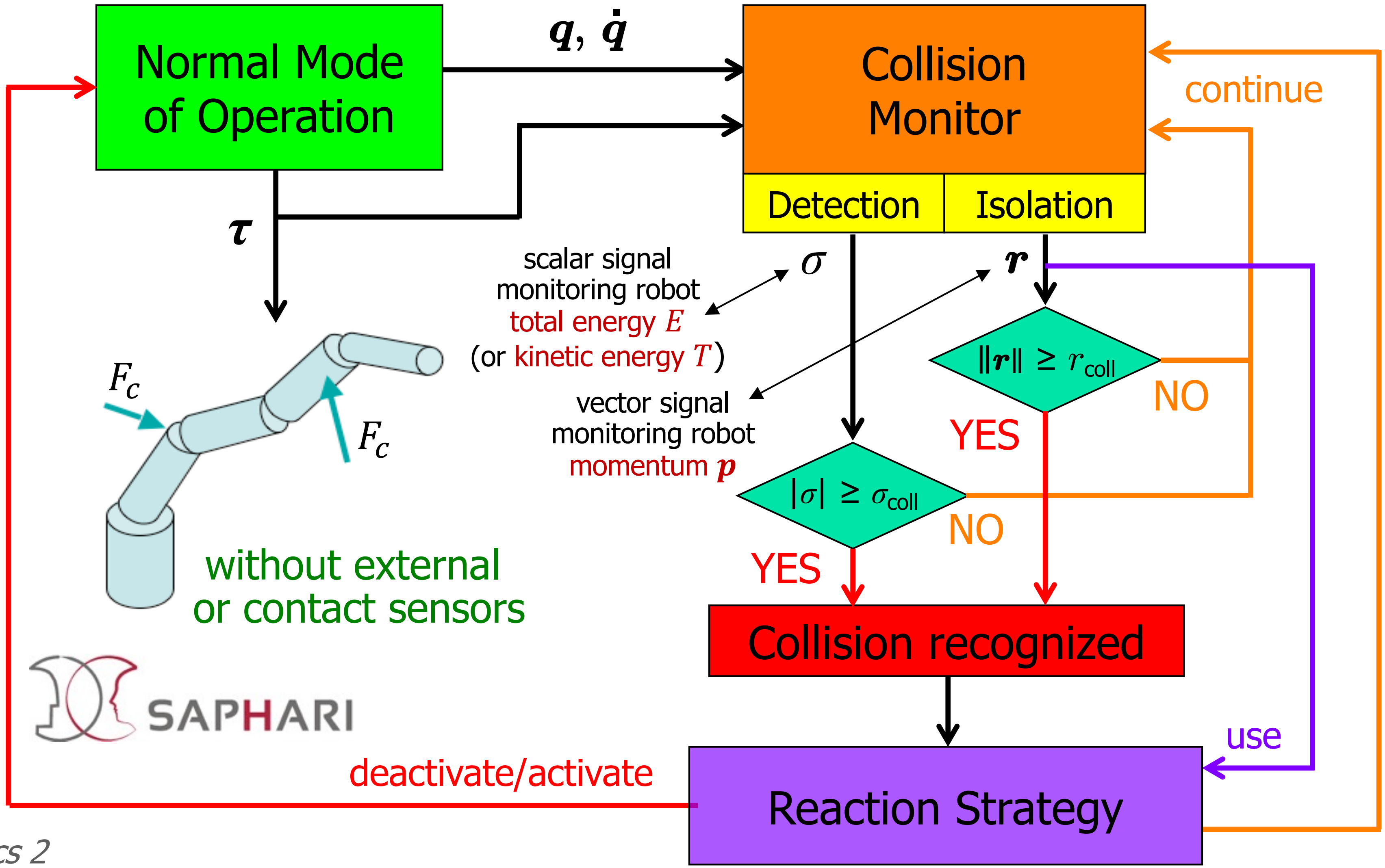
(motor equations with JTS)

# Collision detection and isolation

## "sensorless" residuals

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

(both terms unknown)



# Block diagram of the residual generator

## momentum-based collision detection and isolation

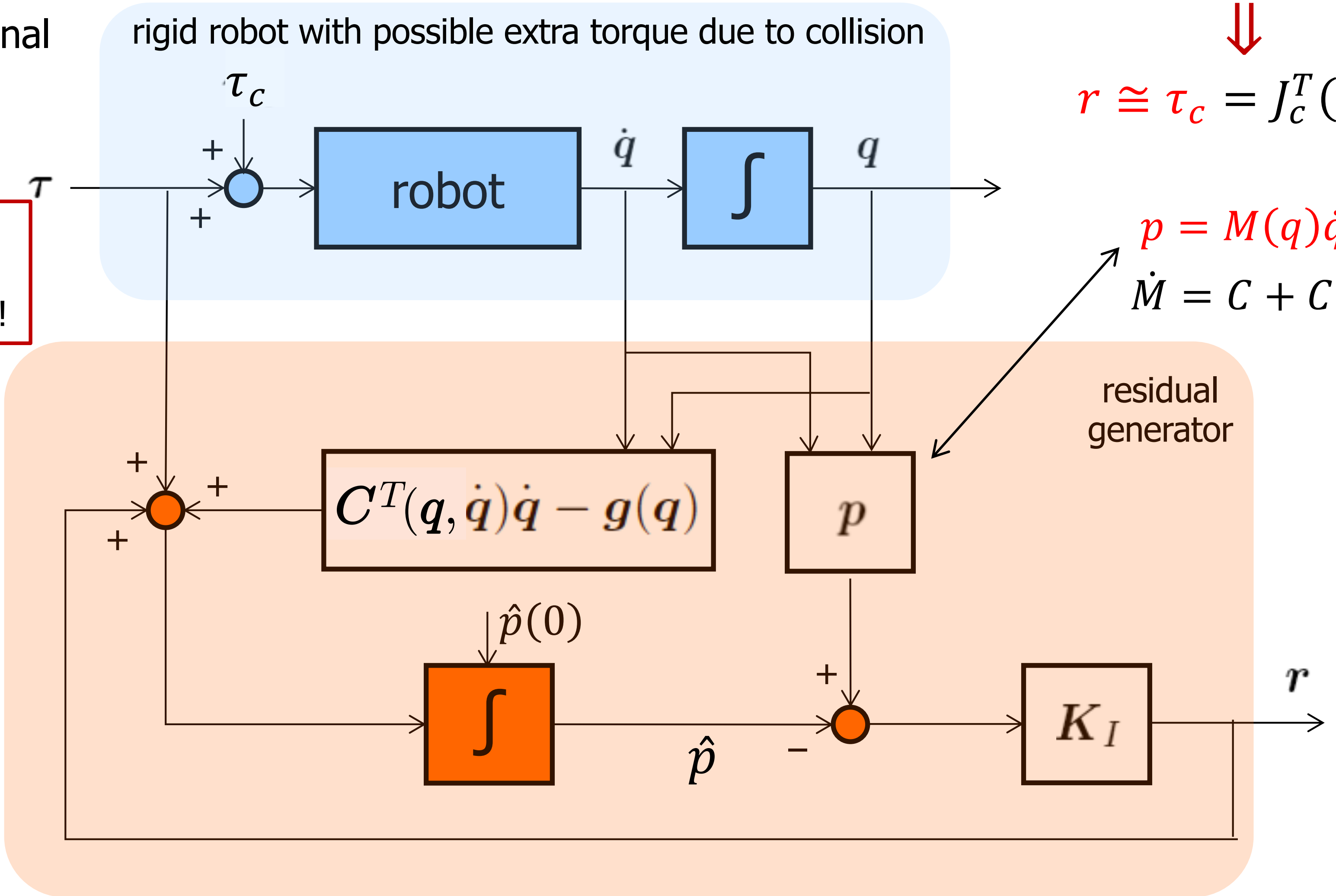
$$r(t) = K_I\left(p(t) - \int_0^t (\tau + C^T(q,\dot{q})\dot{q} - g(q) + r)ds - p(0)\right) \Rightarrow \boxed{\dot{r} = K_I(\tau_c - r)}$$

$K_I > 0$, diagonal
$r(0) = 0$

$\Downarrow$

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

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




$p = M(q)\dot{q}$
$\dot{M} = C + C^T$

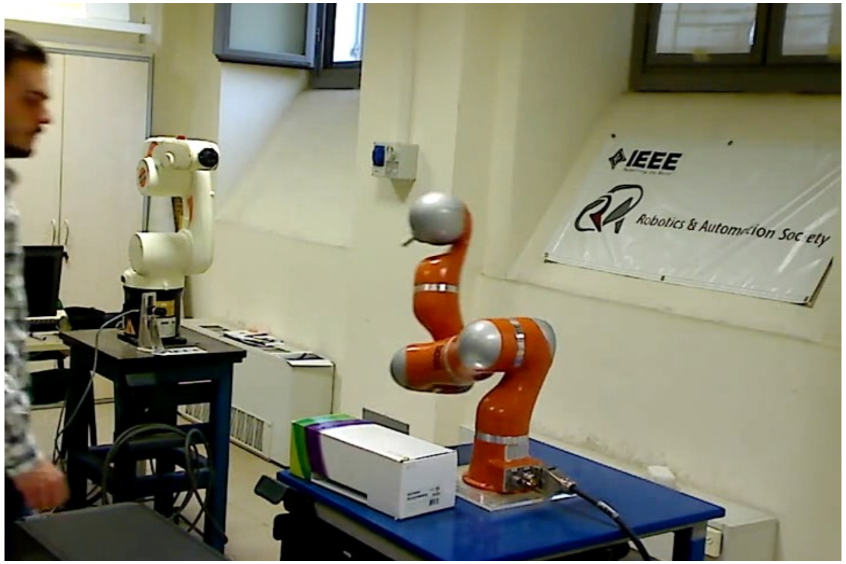
initialization of integrators
$\hat{p}(0) = p(0)$
(**zero** if robot starts at rest)

# Collision detection and isolation

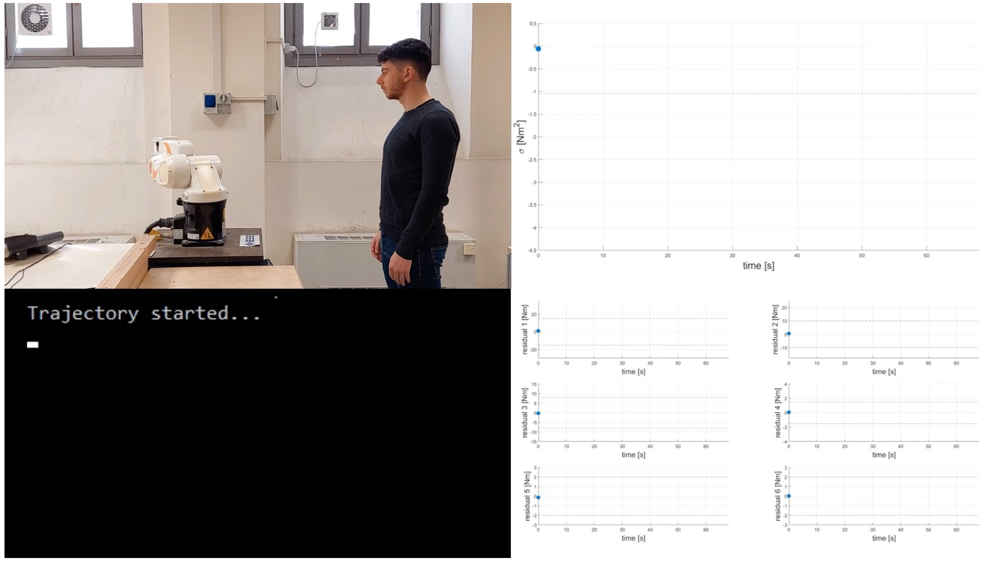
## experiments with different robots over the years …

DLR III - **2006**


Neura - **2023**


LWR IV - **2015**



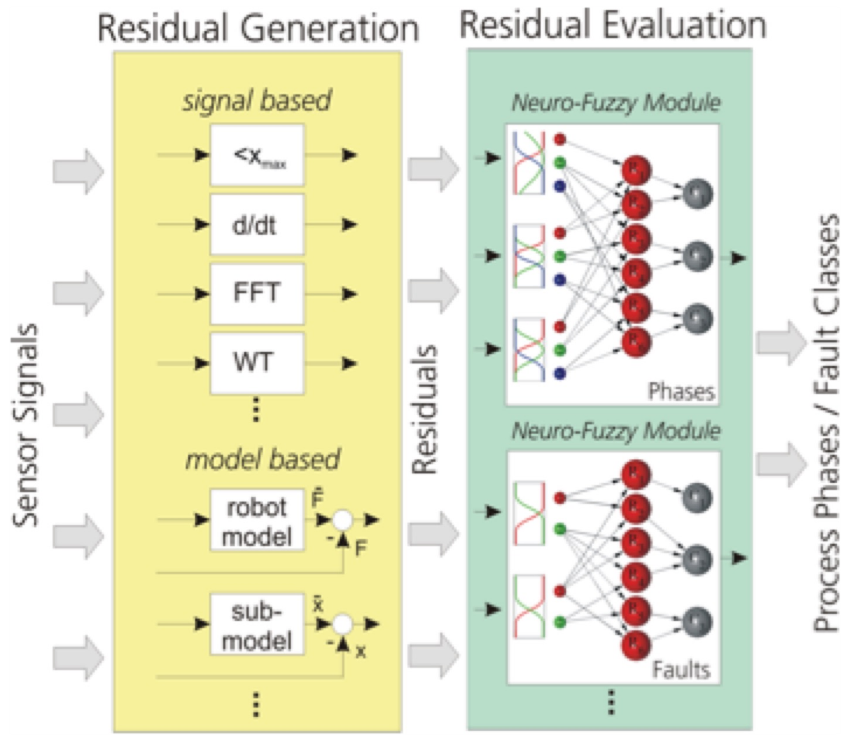

KUKA KR5 – **2022**

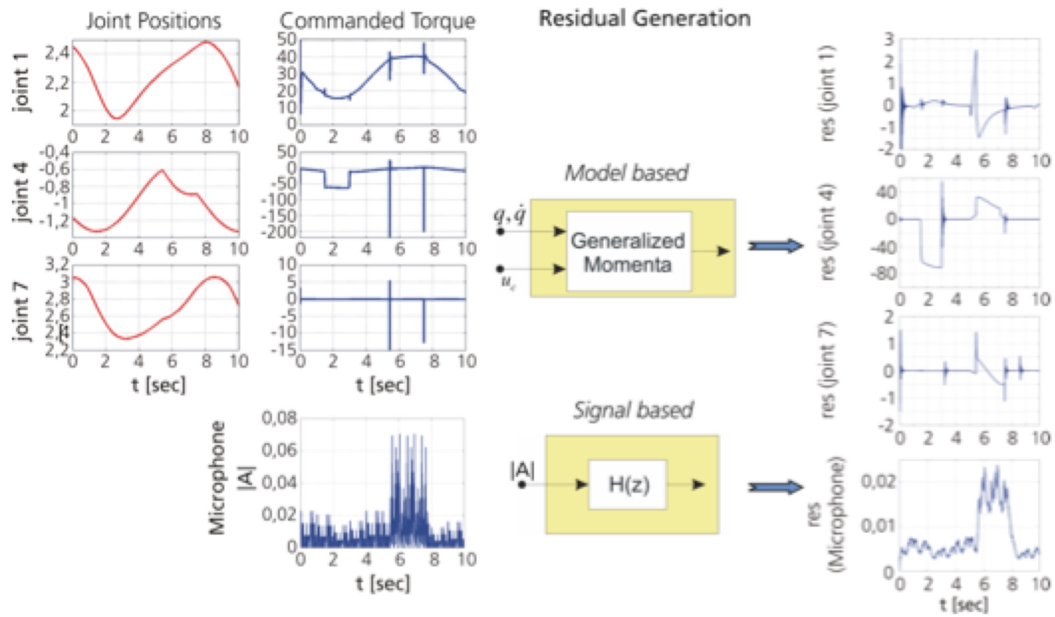
4 videos

# 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)

obtaining thus the "best of both worlds"



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