



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)



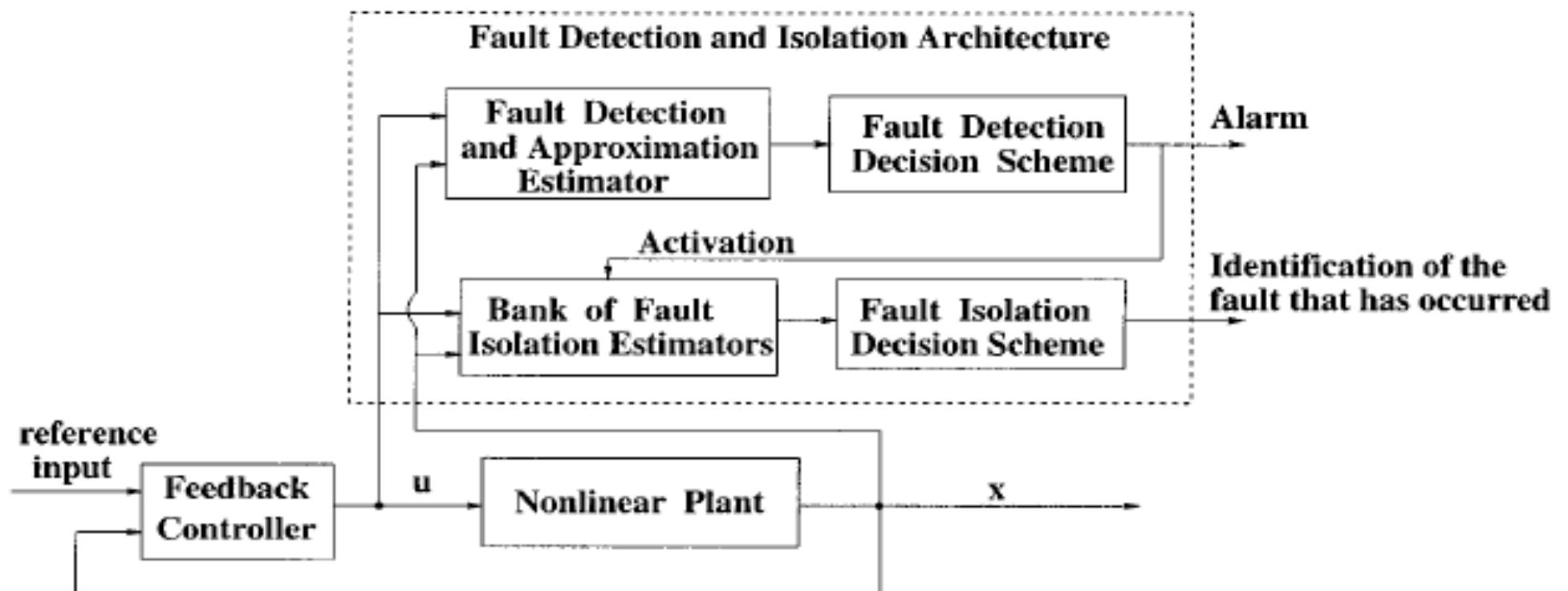
Fault diagnosis problems - 2

- 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

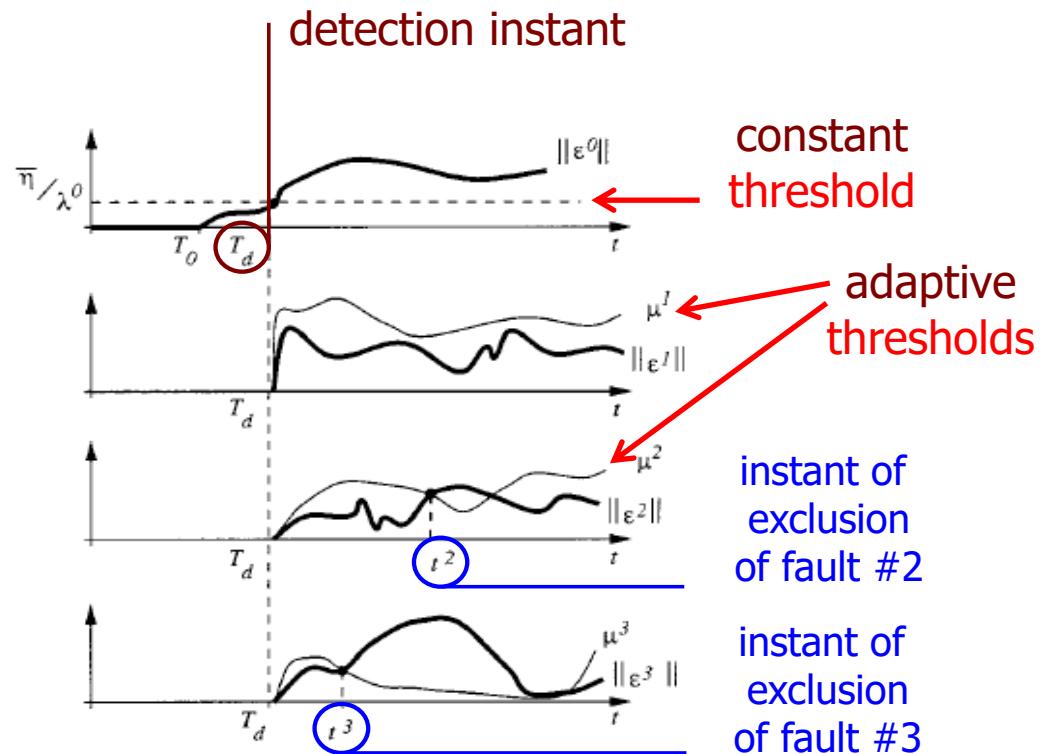
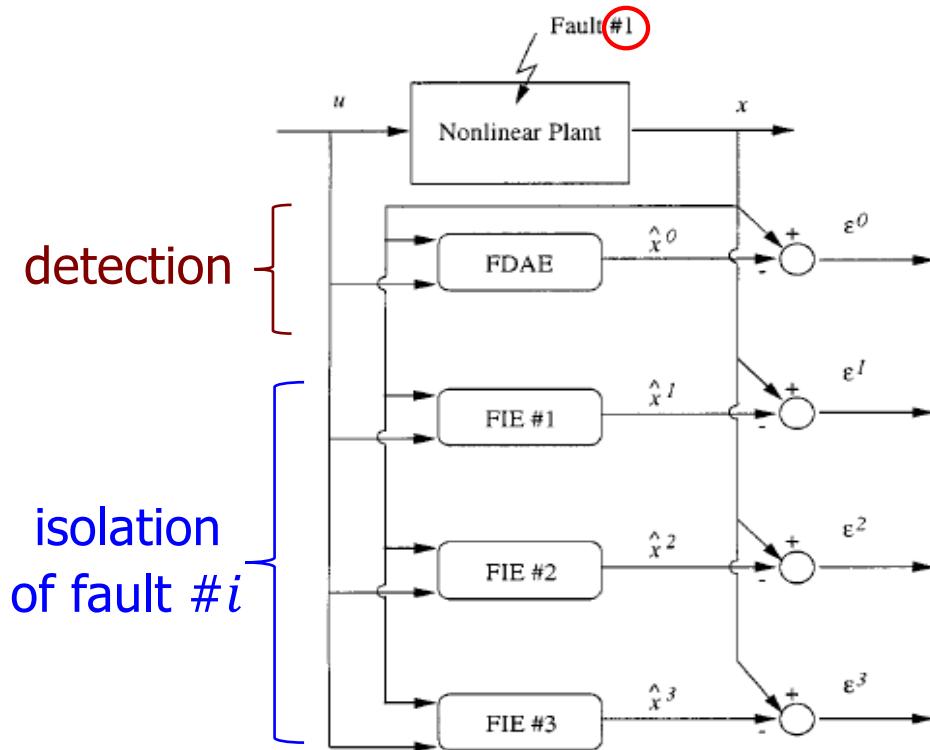
- bank of $n + 1$ (model-based) estimators
 - 1 for **detection** of a faulty condition
 - n for **isolation** of the specific (in general, **modeled**) fault





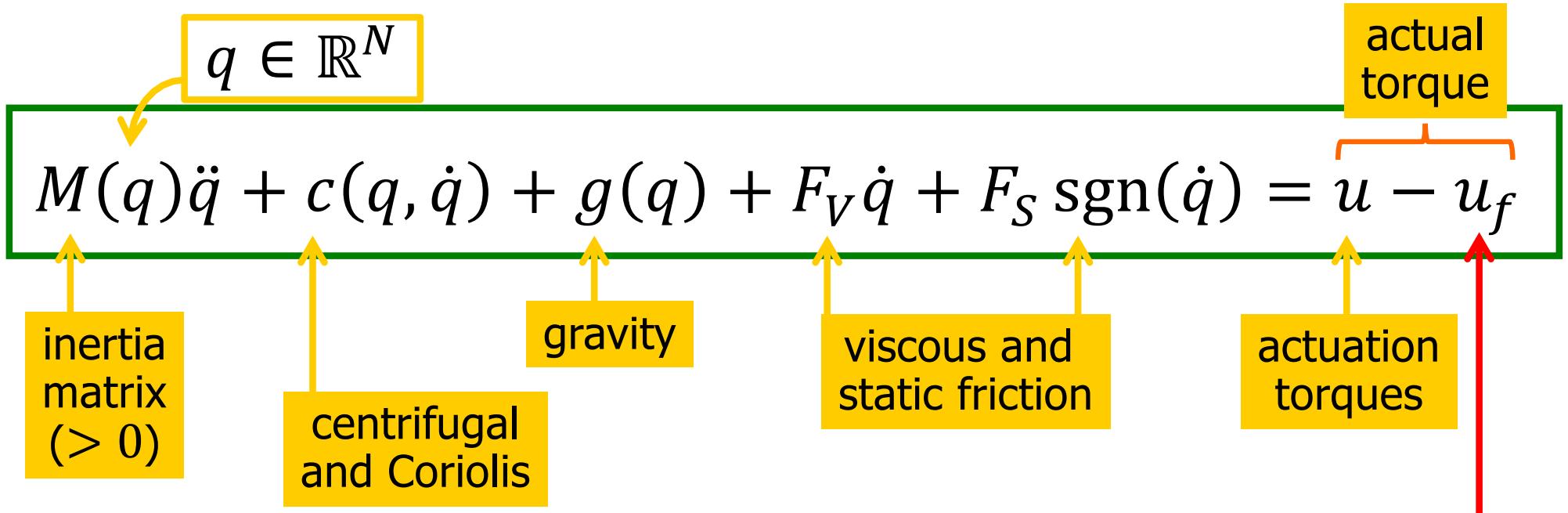
Some terminology

- 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



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 $u_{f,i} = u_i - \operatorname{sgn}(u_i) u_{i,max}$
- bias $u_{f,i} = b_i$ Ex: ??
- block $u_{f,i} = \dots$
- ... 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

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

with associated dynamic equation

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

decoupled components
relative to the single fault inputs

exploiting structure
of centrifugal and
Coriolis terms

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

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



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 $\tau_i = 1/k_i$

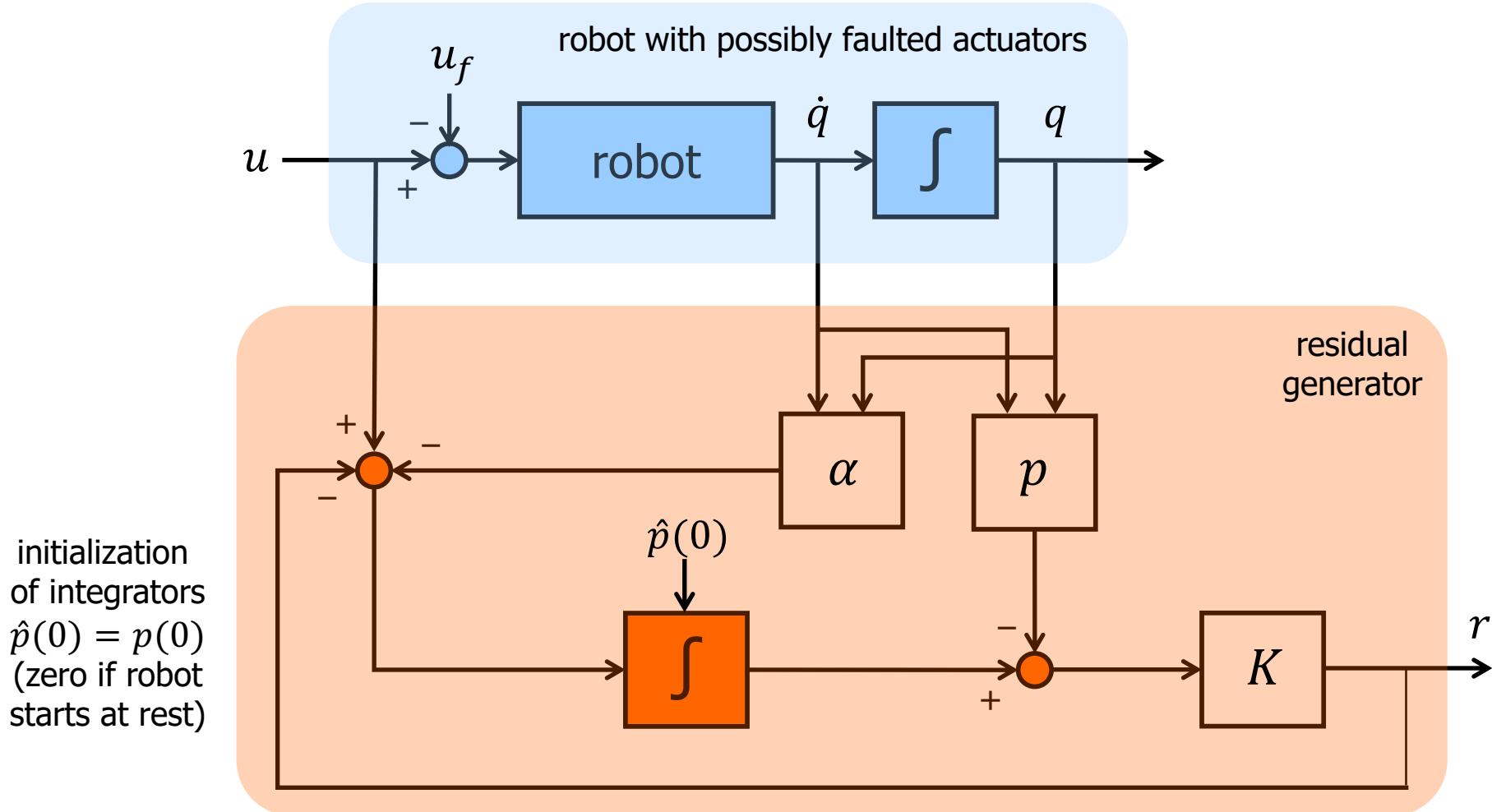
$$\dot{r} = -Kr + Ku_f$$

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



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



Residual generator as “disturbance observer”

from the
block diagram...

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



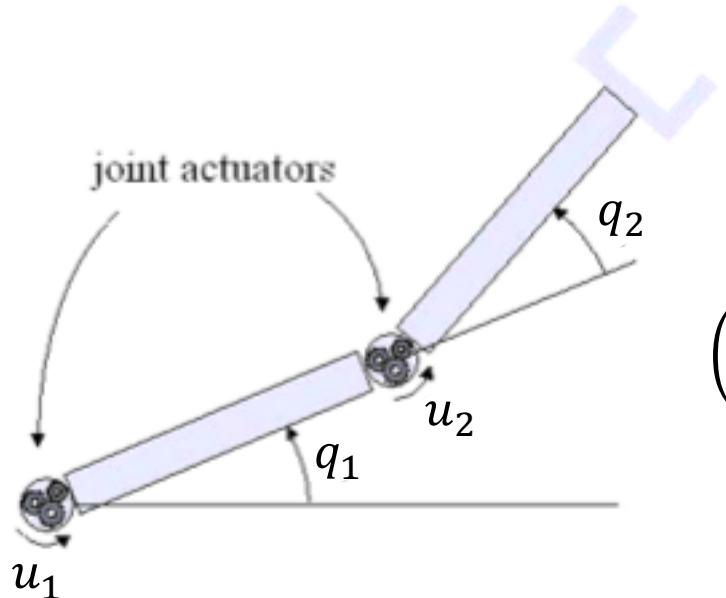
dynamic observer of the unknown actuation faults
($r \approx \rightarrow u_f$ = external disturbances)
with **linear** error dynamics (for constant u_f)

$$\begin{aligned}e_{obs} &= u_f - r \quad \rightarrow \quad \dot{e}_{obs} = \dot{u}_f - \dot{r} = \dot{u}_f - K(\dot{\hat{p}} - \dot{p}) \\ &= \dot{u}_f - K((u - \alpha - r) - (u - \alpha - u_f)) \\ &= \dot{u}_f - K(u_f - r) = \dot{u}_f - K e_{obs} \cong -K e_{obs}\end{aligned}$$



A worked-out example

- planar 2R robot under gravity



dynamic model (without friction)

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

$\overbrace{\quad\quad\quad}^{= S(q, \dot{q})\dot{q}}$

$$\begin{pmatrix} a_1 + 2a_2c_2 & a_3 + a_2c_2 \\ a_3 + a_2c_2 & a_3 \end{pmatrix} \begin{pmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{pmatrix} + \begin{pmatrix} -a_2(2\dot{q}_1 + \dot{q}_2)\dot{q}_2s_2 \\ a_2\dot{q}_1^2s_2 \end{pmatrix} + \begin{pmatrix} a_4c_1 + a_5c_{12} \\ a_5c_{12} \end{pmatrix} = \begin{pmatrix} u_1 - u_{f,1} \\ u_2 - u_{f,2} \end{pmatrix}$$

computation of the residual vector

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

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

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

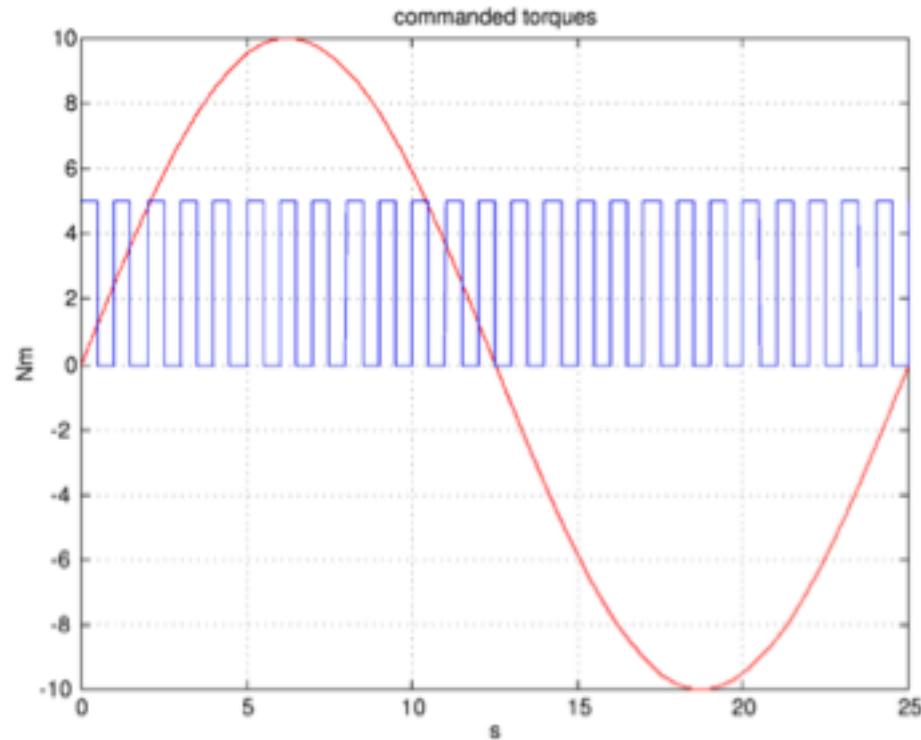
$$\begin{aligned} \alpha_2 &= -\frac{1}{2} \dot{q}^T \frac{\partial M(q)}{\partial q_2} \dot{q} + g_2(q) \\ &= a_2(\dot{q}_1 + \dot{q}_2)\dot{q}_1s_2 + a_5c_{12} \end{aligned}$$



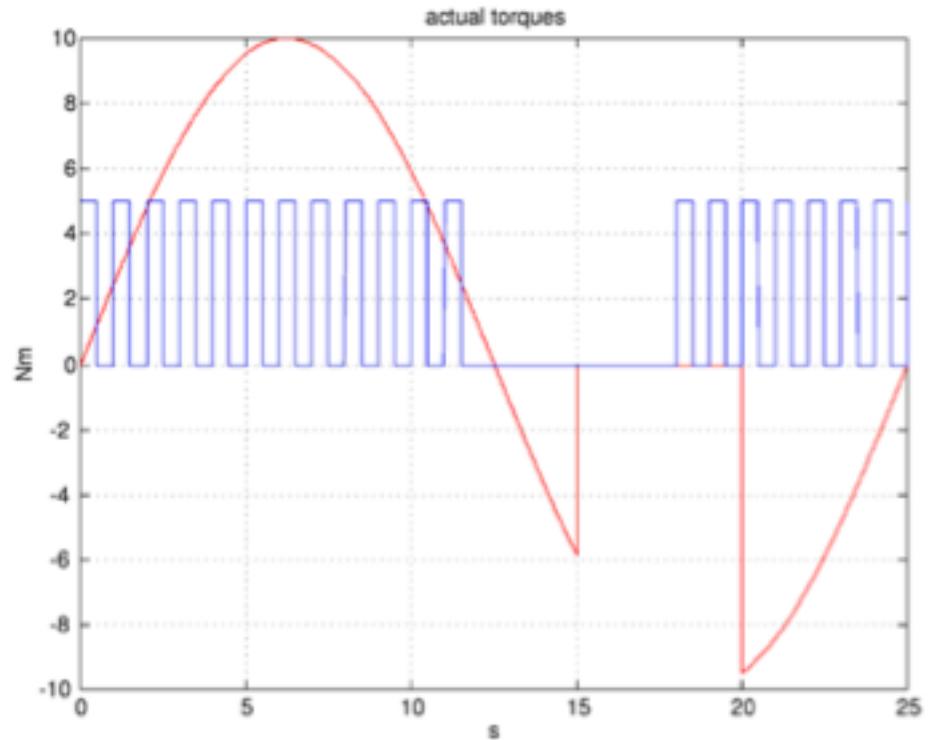
Faults on both actuators

(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)

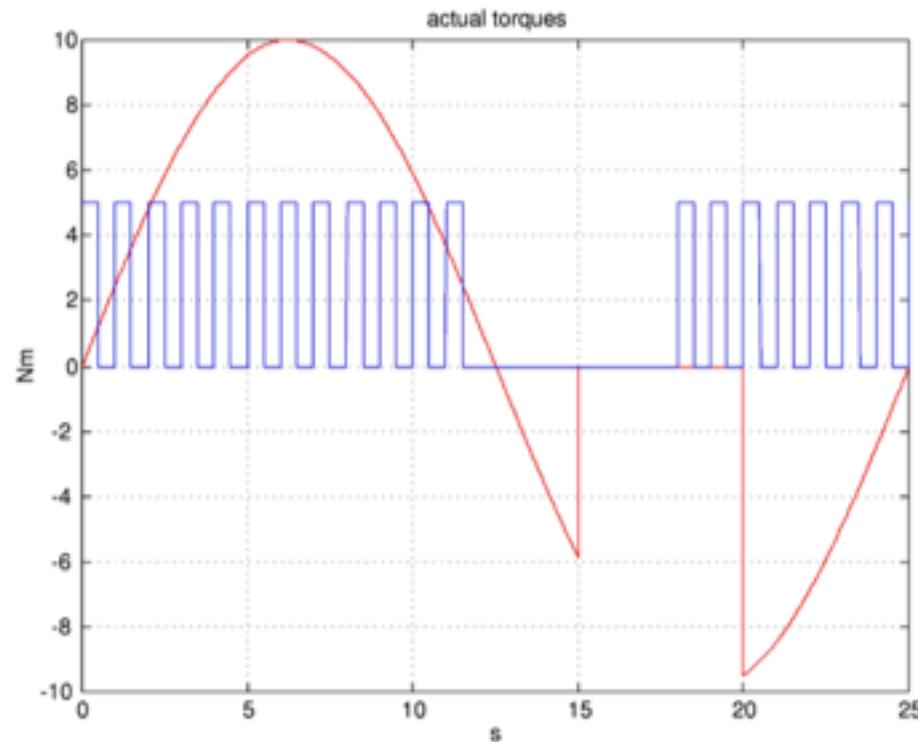


time interval of
fault **concurrence**
 $t \in [15 \div 18]$ sec



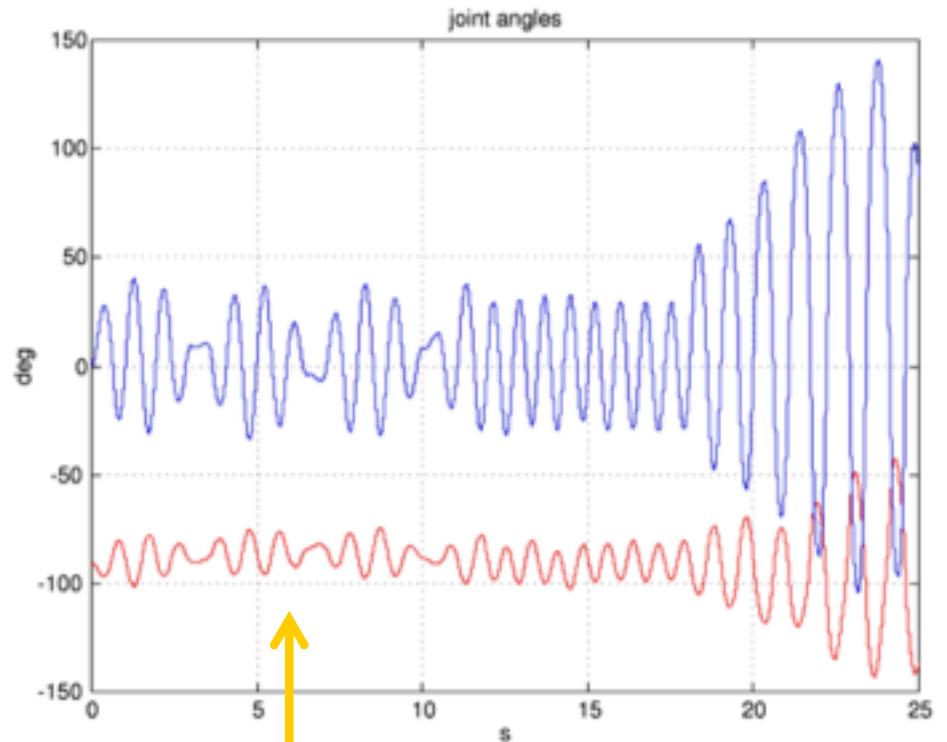
First simulation

actual torques (to the robot)



- = first joint
- = second joint

(measured) joint positions

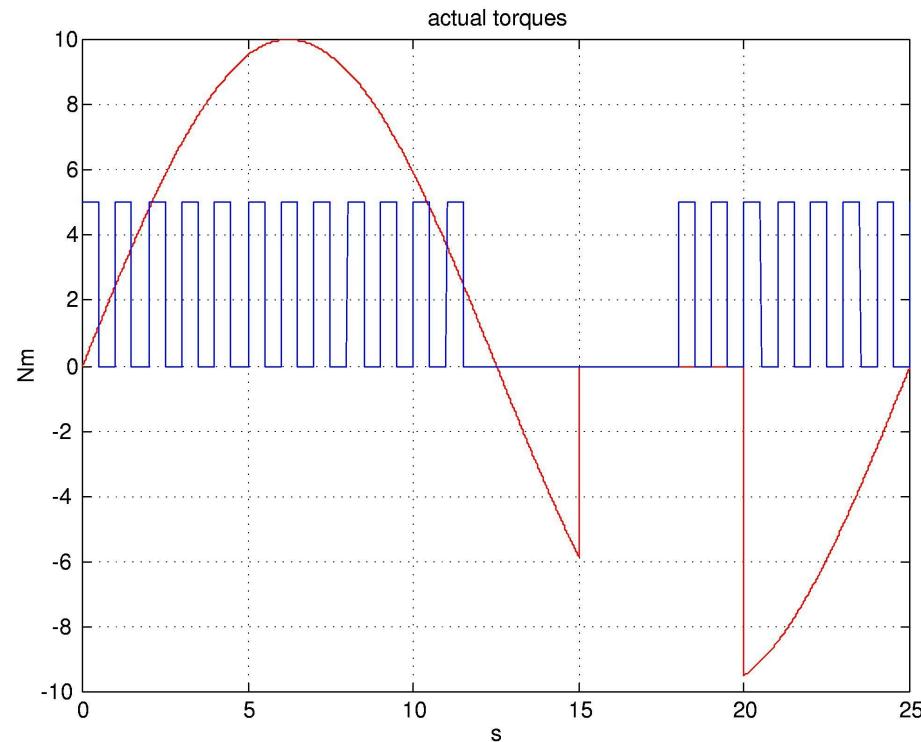


no clear evidence of faults in the dynamic evolution of the system!



First simulation – FDI

actual torques (to the robot)

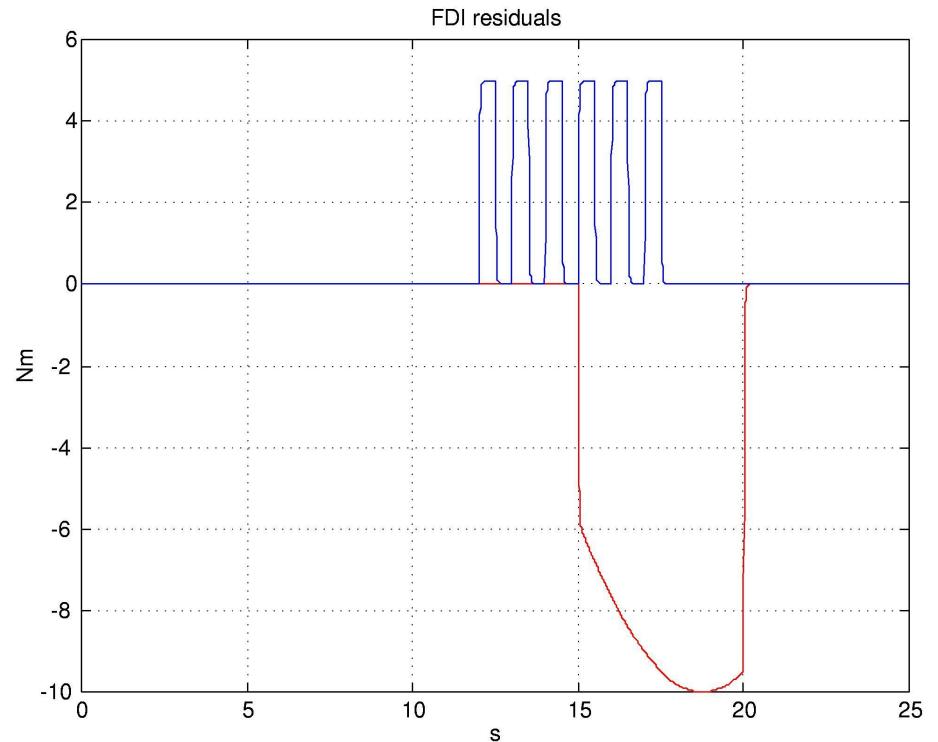


— = first joint

— = second joint

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

residuals



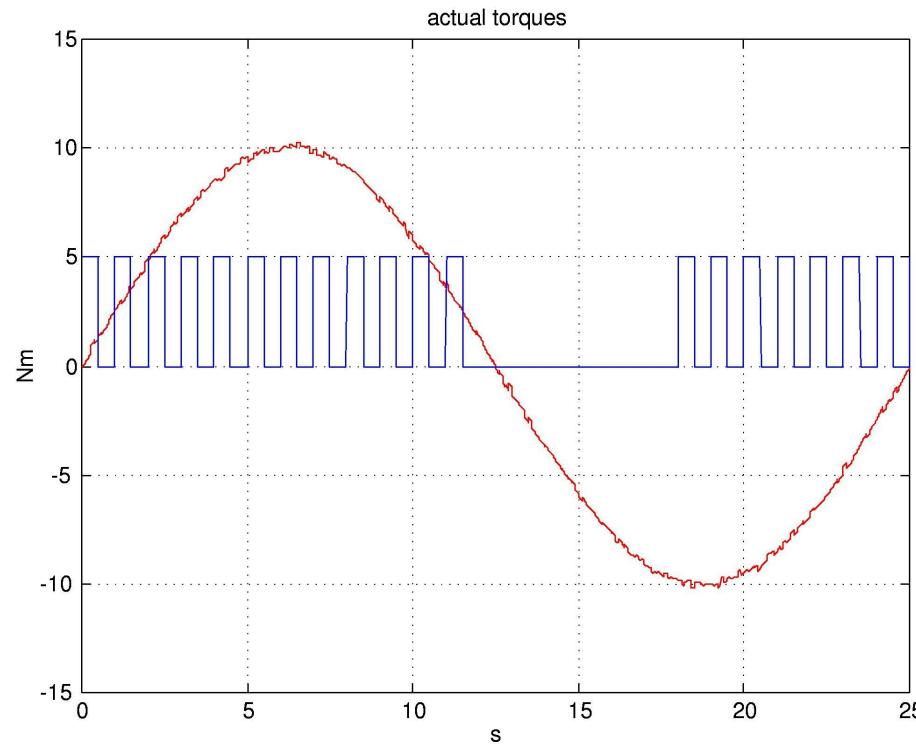
residuals reconstruct the
“missing” parts of the torques
(identification property!)



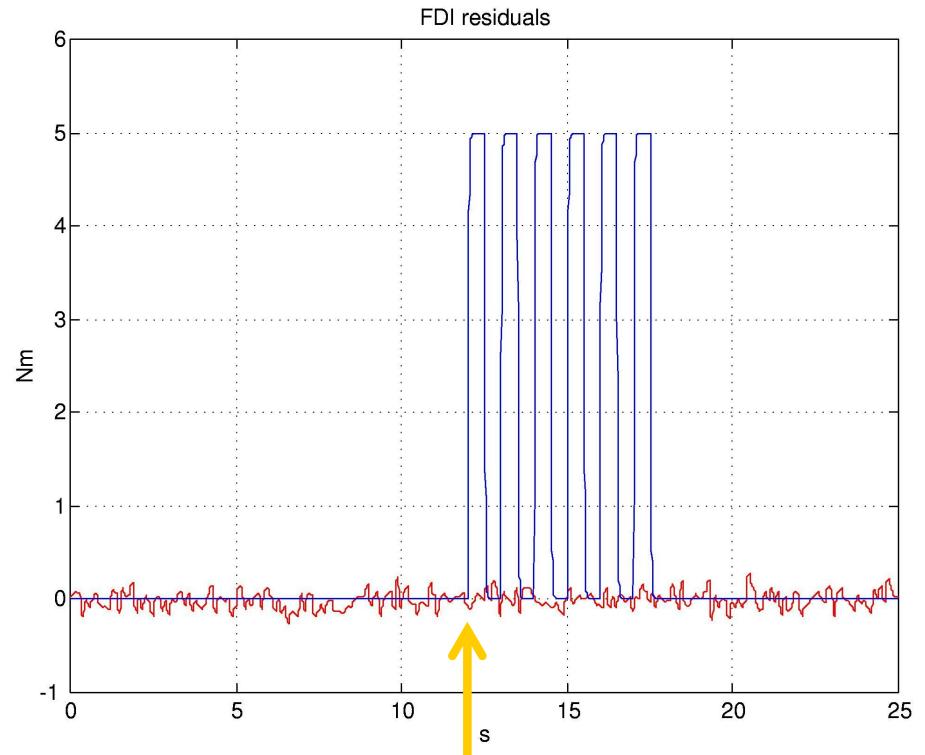
Second simulation – FDI

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

actual torques (to the robot)



residuals



— = first joint

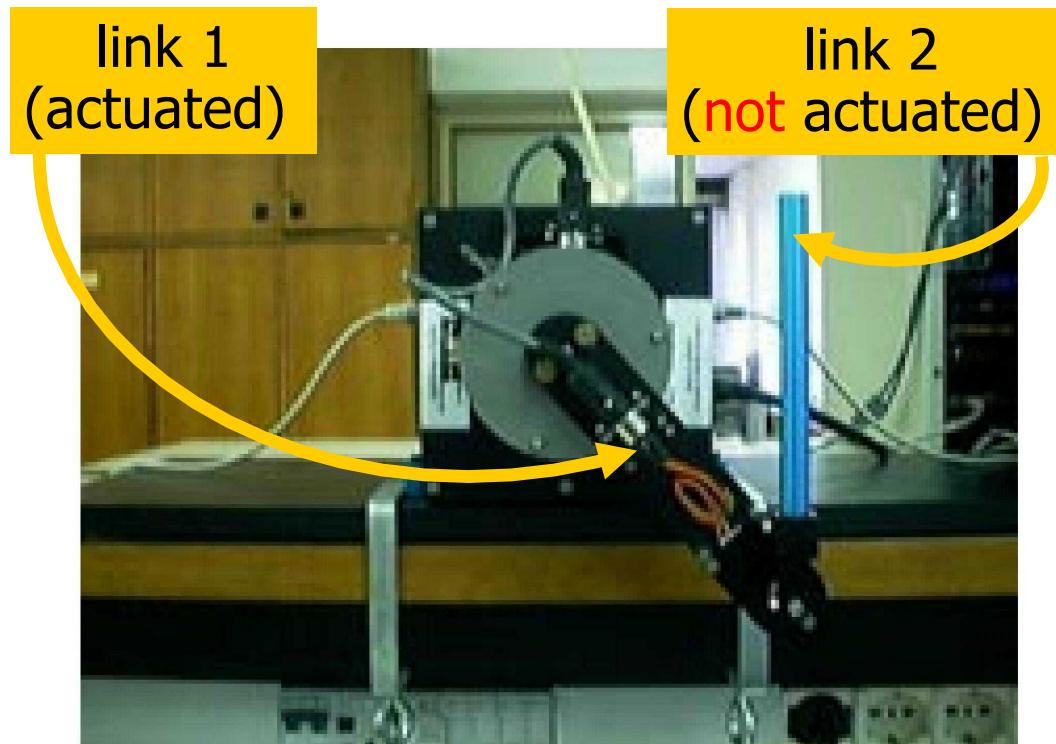
— = second joint (fault for $t \in [12 \div 18]$ sec)

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

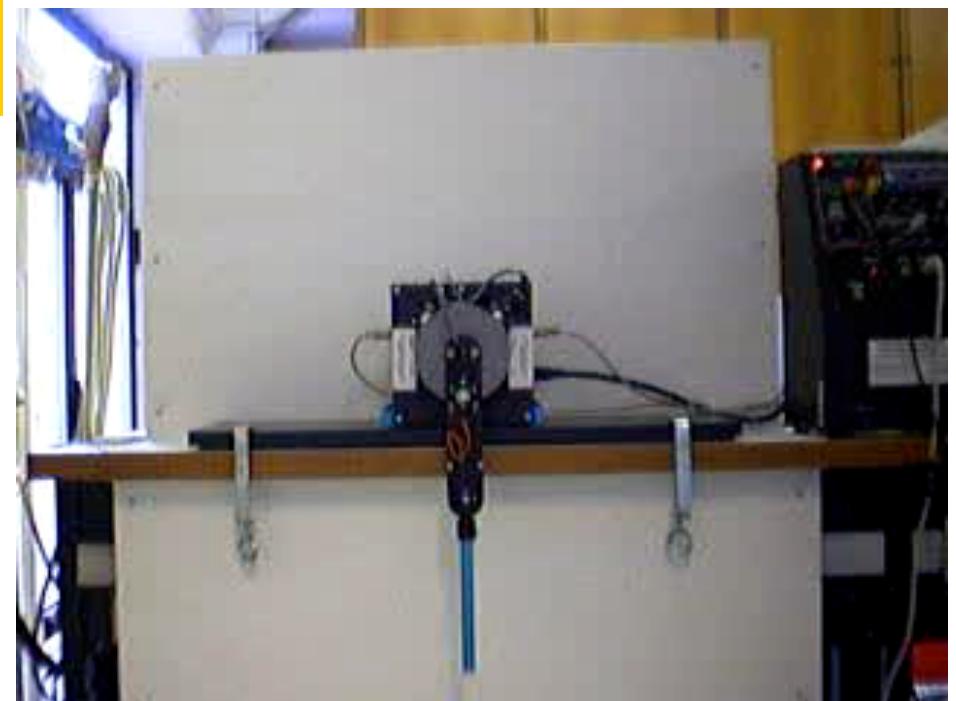


Experimental setup

Quanser Pendubot



with encoders on both joints



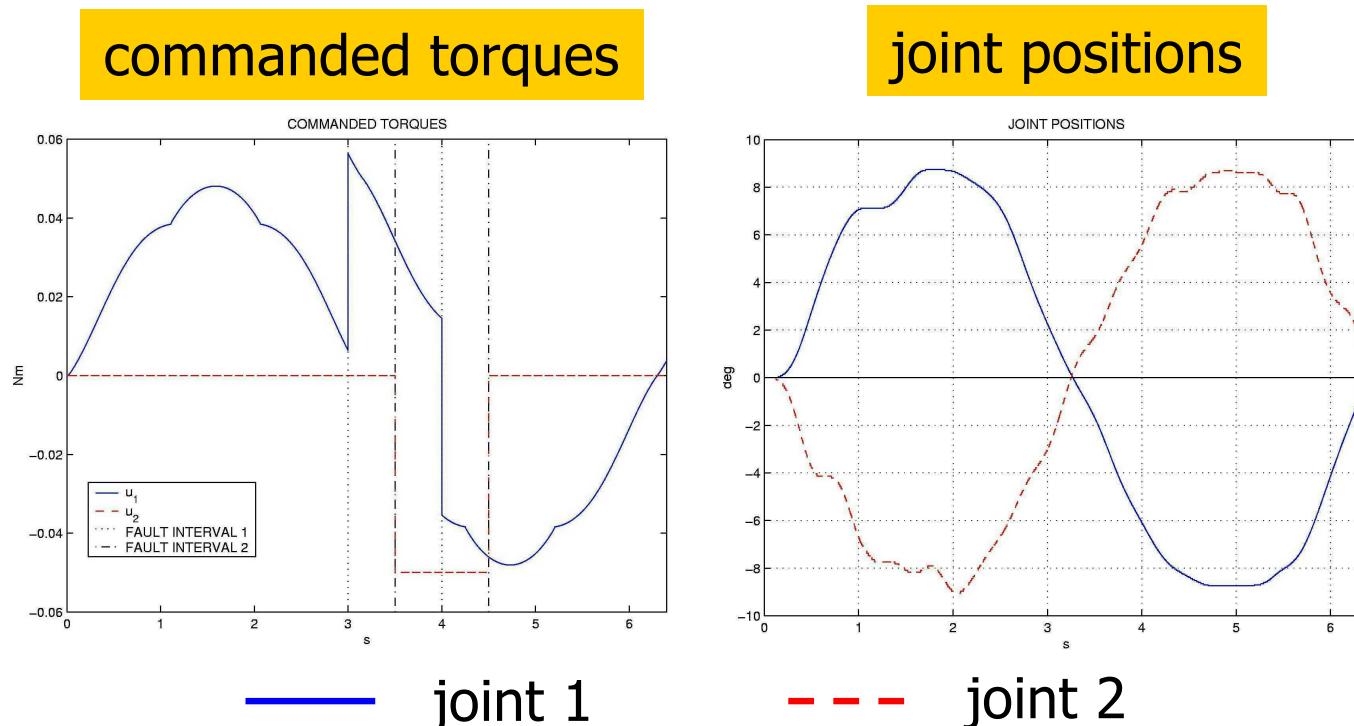
nonlinear control for swing-up

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

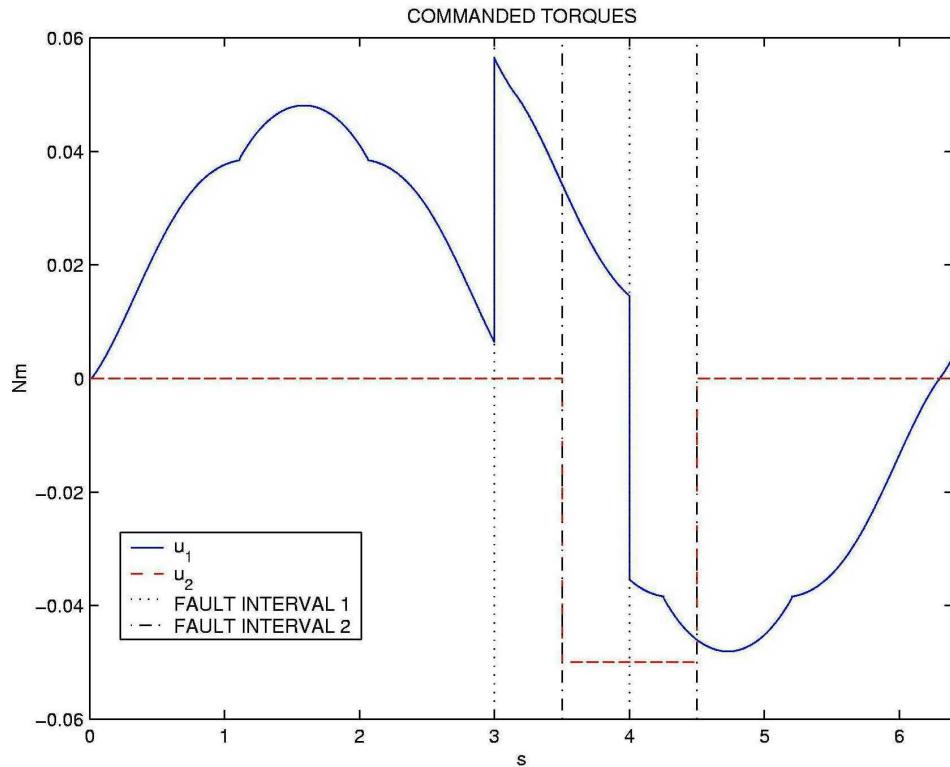
- motor 1 driven by sinusoidal voltage of period 2π sec (open loop)
- **bias fault** on u_1 for $t \in [3 \div 4]$ sec
- **total fault** on second joint for $t \in [3.5 \div 4.5]$ sec (a constant torque is requested, but **no motor at the joint to provide 0.05 Nm...**)
- **fault concurrency** for $t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



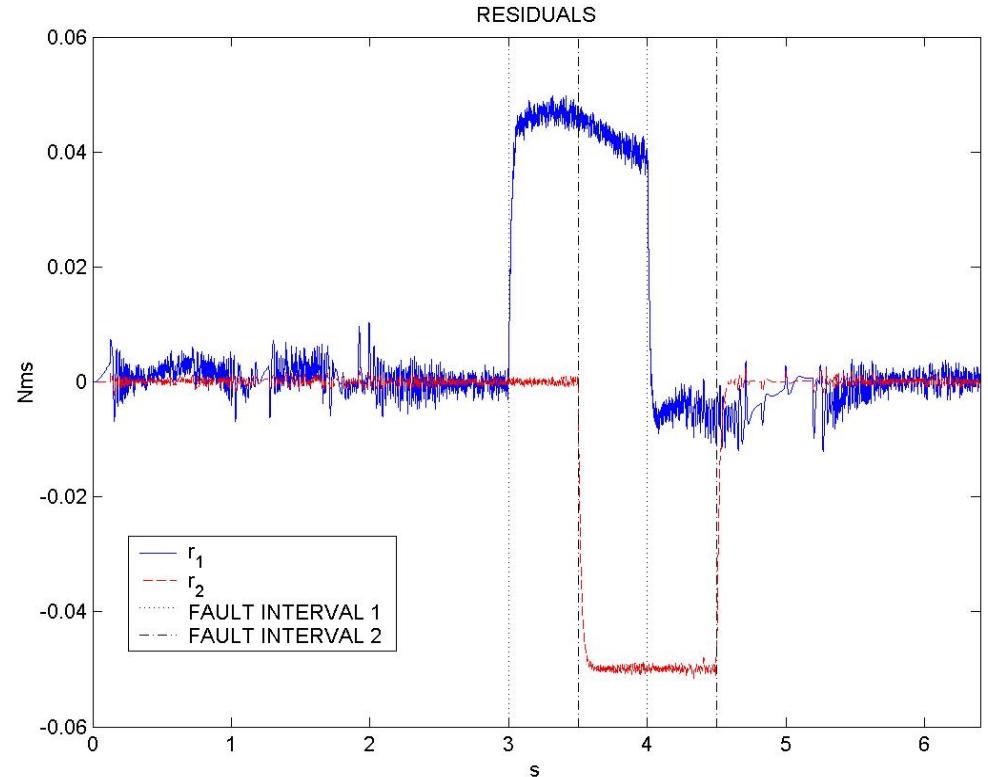


First experiment – FDI

commanded torques



residuals

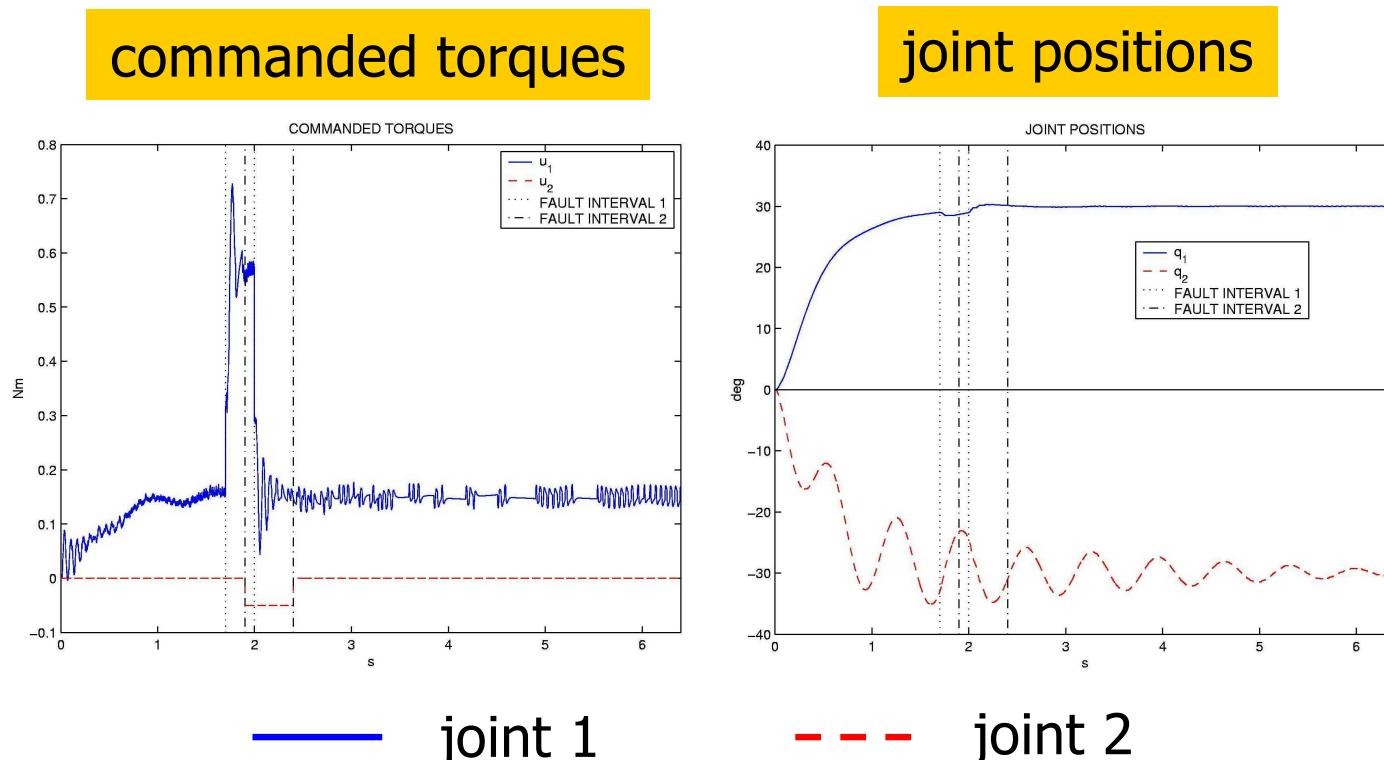


— joint 1

- - - joint 2

Second experiment

- position regulation of the first joint at $q_{d1} = 30^\circ$ (**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

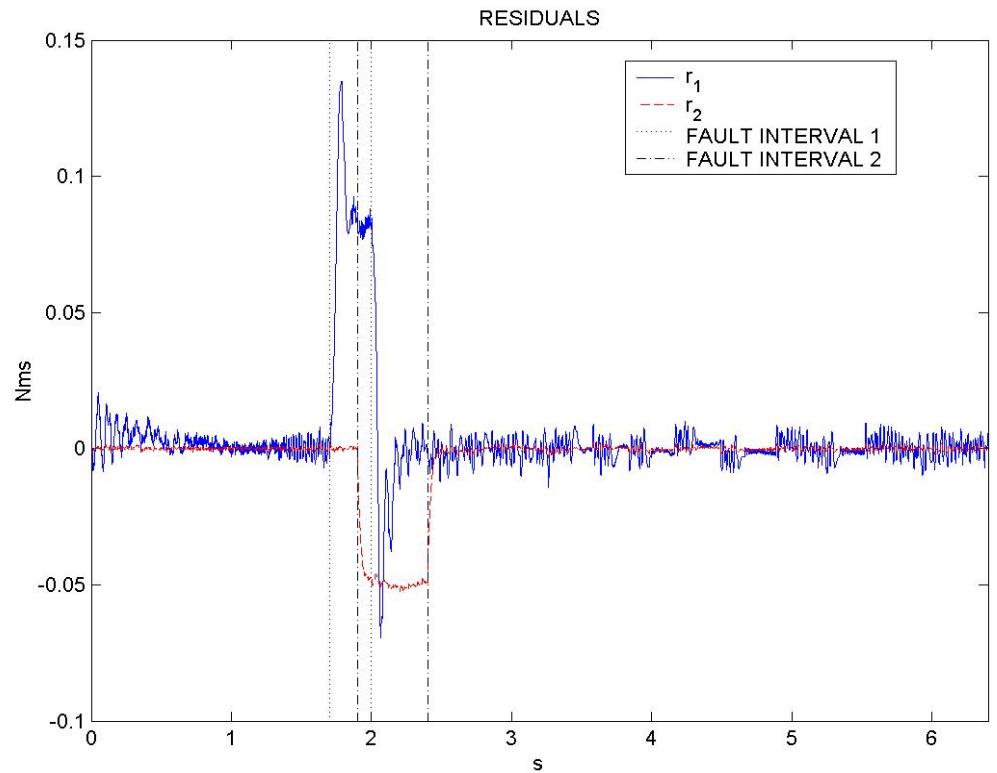
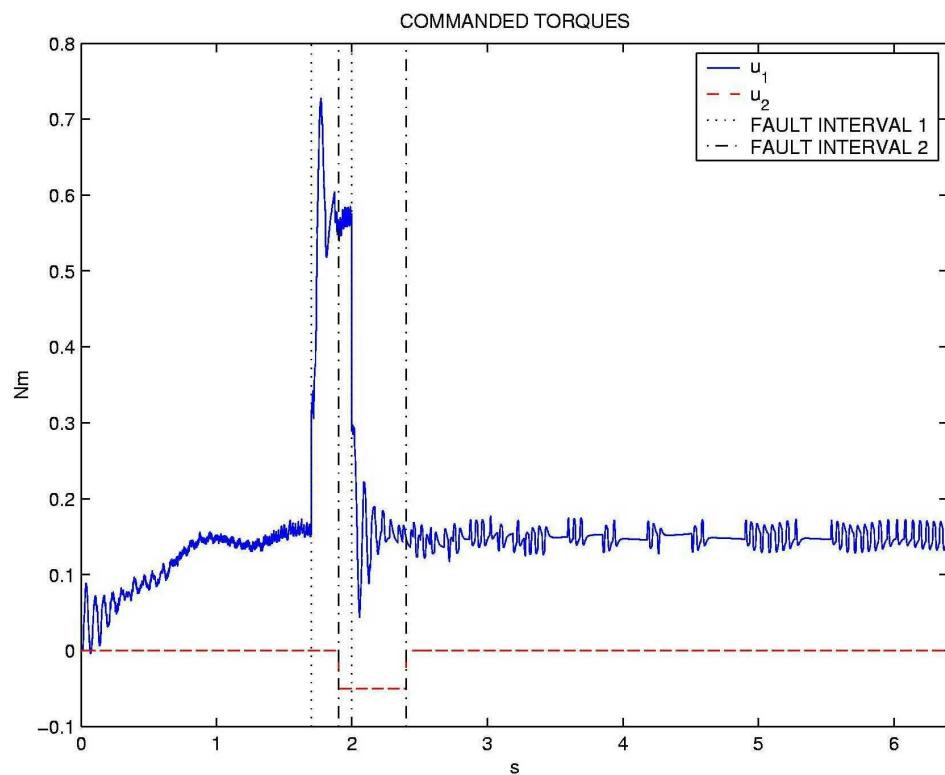




Second experiment – FDI

commanded torques

residuals

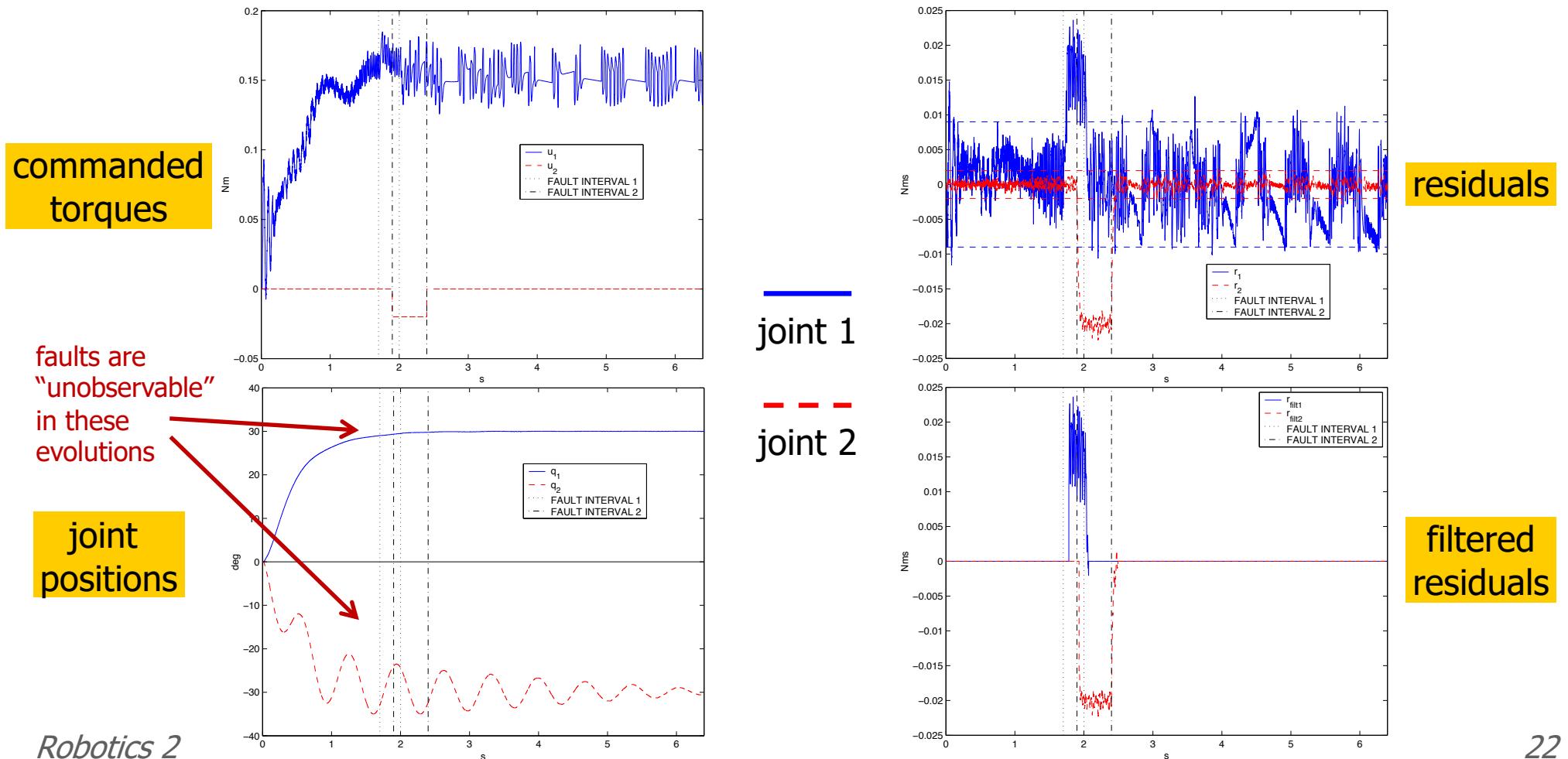


— joint 1

- - - 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]





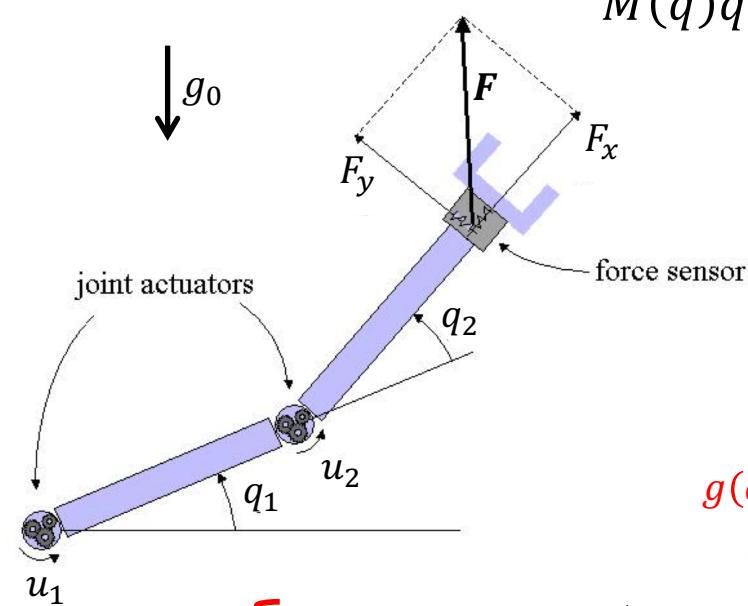
Extensions

- 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**, so as 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
 $J^{ad} = \det(J) \cdot J^{-1}$
 \Rightarrow singularity robust!

time derivative of transposed Jacobian adjoint

robot inertia

input torque

$$g(q) - S^T(q, \dot{q})\dot{q}$$

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

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

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

$$\det J^T(q)$$

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

Ex: prove this expression!

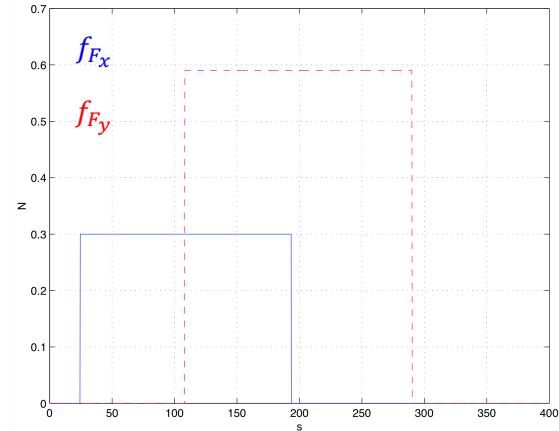




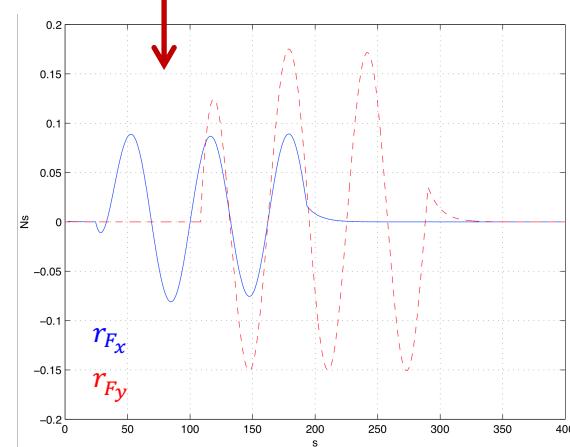
Isolation of F/T sensor faults

- simulation on the 2R robot

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 $t \in [109 \div 285]$



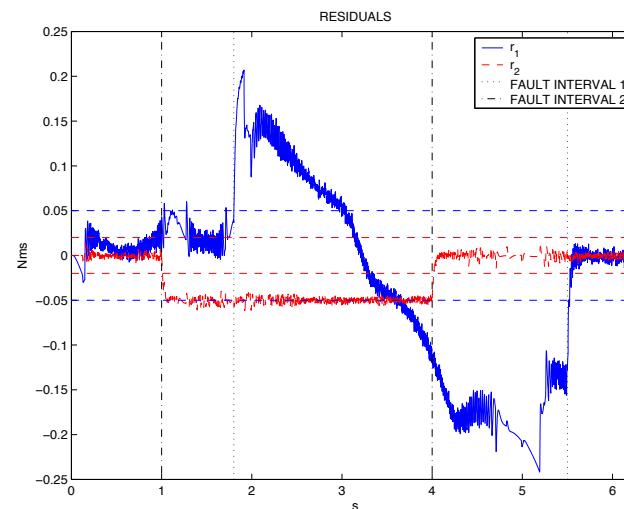
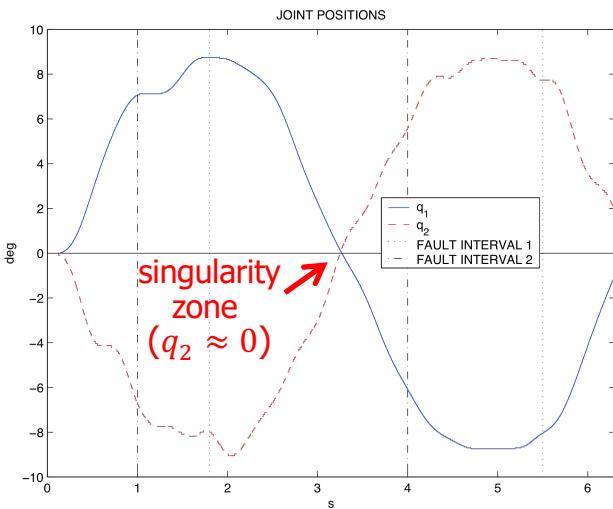
q_2 is tracking a sinusoid ($A = \pi/8$ rad, $\omega = 0.1$ rad/s)



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

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

evolution
of joint
variables



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

$(J^T)^{ad} \rightarrow \text{diag}\{s_2, 1\} J^{-T}$
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

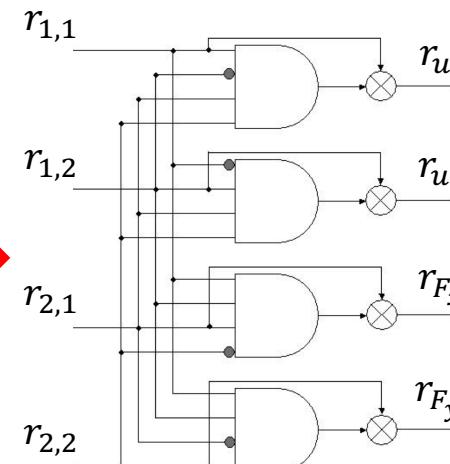
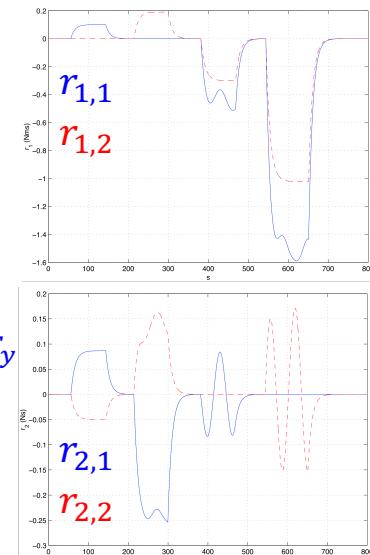
dependence of residuals on considered faults

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

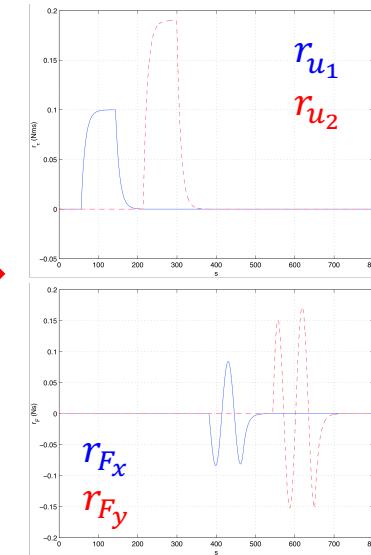
isolation matrix

$r_{2,1} \ r_{2,2}$	11	10	01	00
$r_{1,1} \ r_{1,2}$				
10	f_{u_1}	NA	NA	NA
01	f_{u_2}	NA	NA	NA
11	NC	f_{F_x}	f_{F_y}	NA
00	NA	NA	NA	no fault

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



isolation logics



hybrid residuals allowing isolation of 4 faults

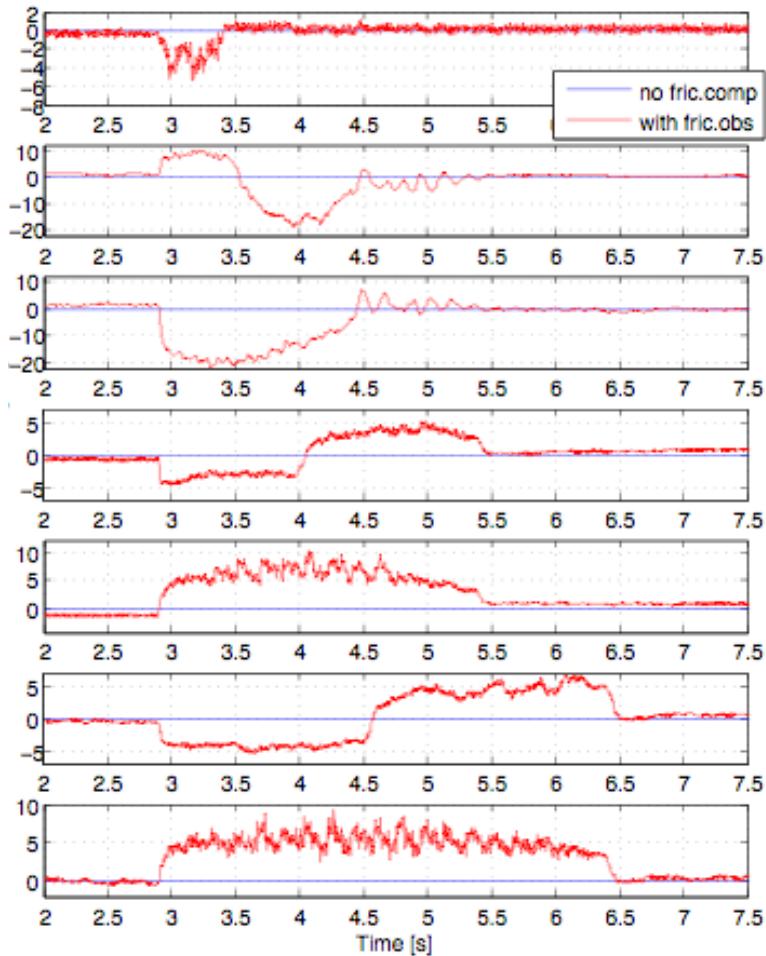


Experiments on friction compensation

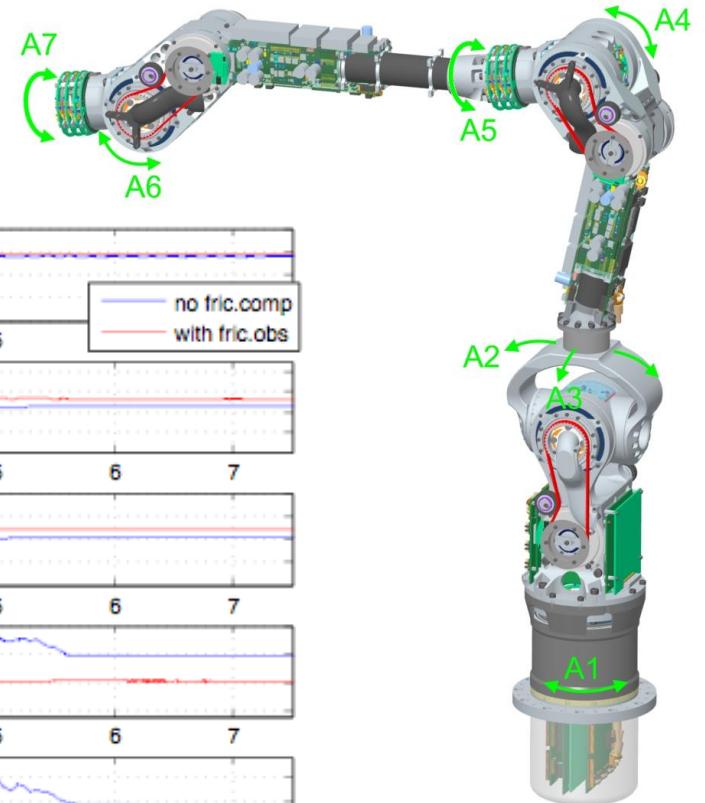
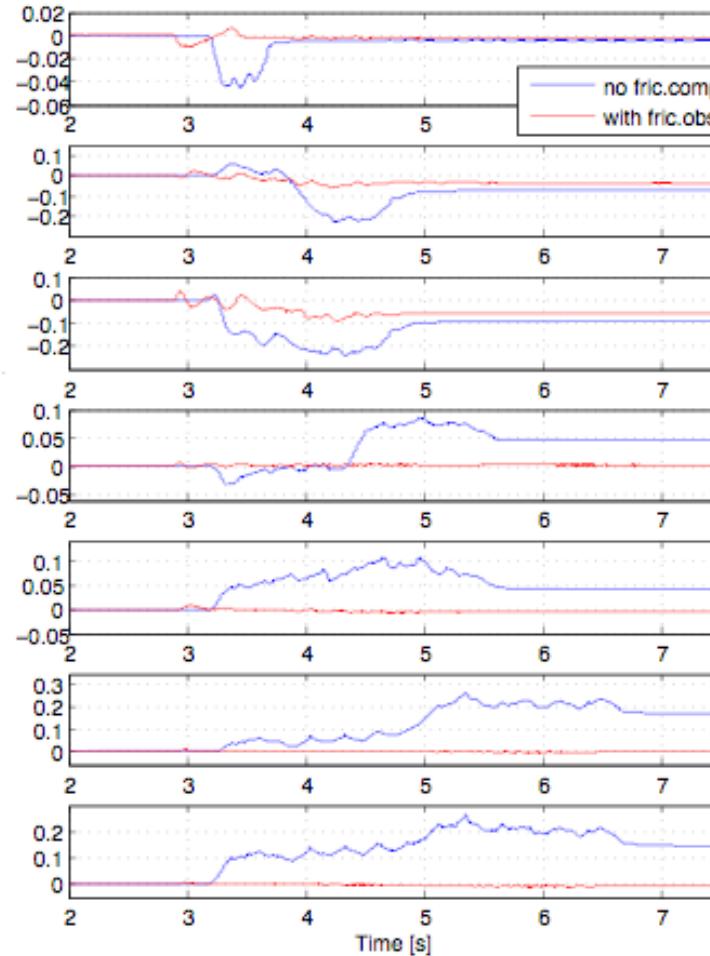
- results on the DLR 7R medical robot

used then on-line
in control law...

friction estimate via residuals



position error

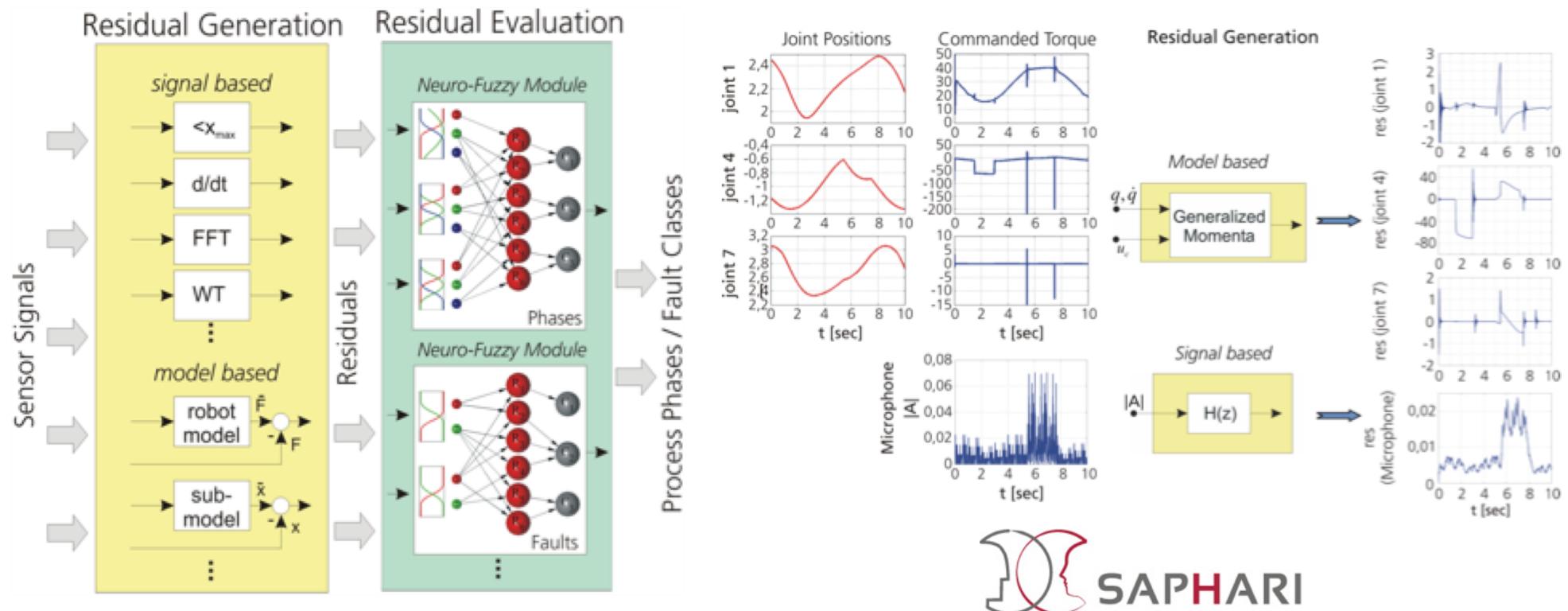


HD at the joints
⇒ elastic joint
dynamic model



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”





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