Robotics 2

Detection and isolation of robot actuator faults

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Fault diagnosis problems - 1

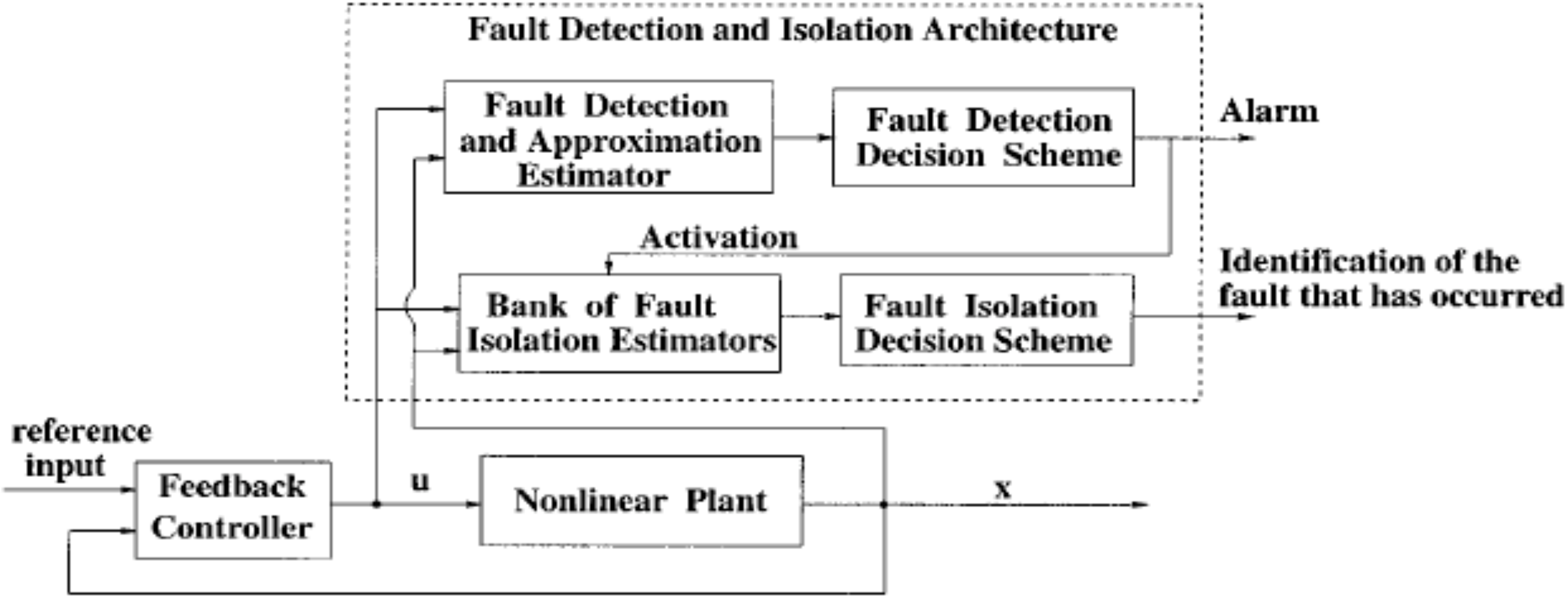
- in the diagnosis of faults possibly affecting a (nonlinear) dynamic system various problems can be formulated
- Fault Detection
  - recognize that the malfunctioning of the (controlled) system is due to the occurrence of a fault (or not proper behavior) affecting some physical or functional component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

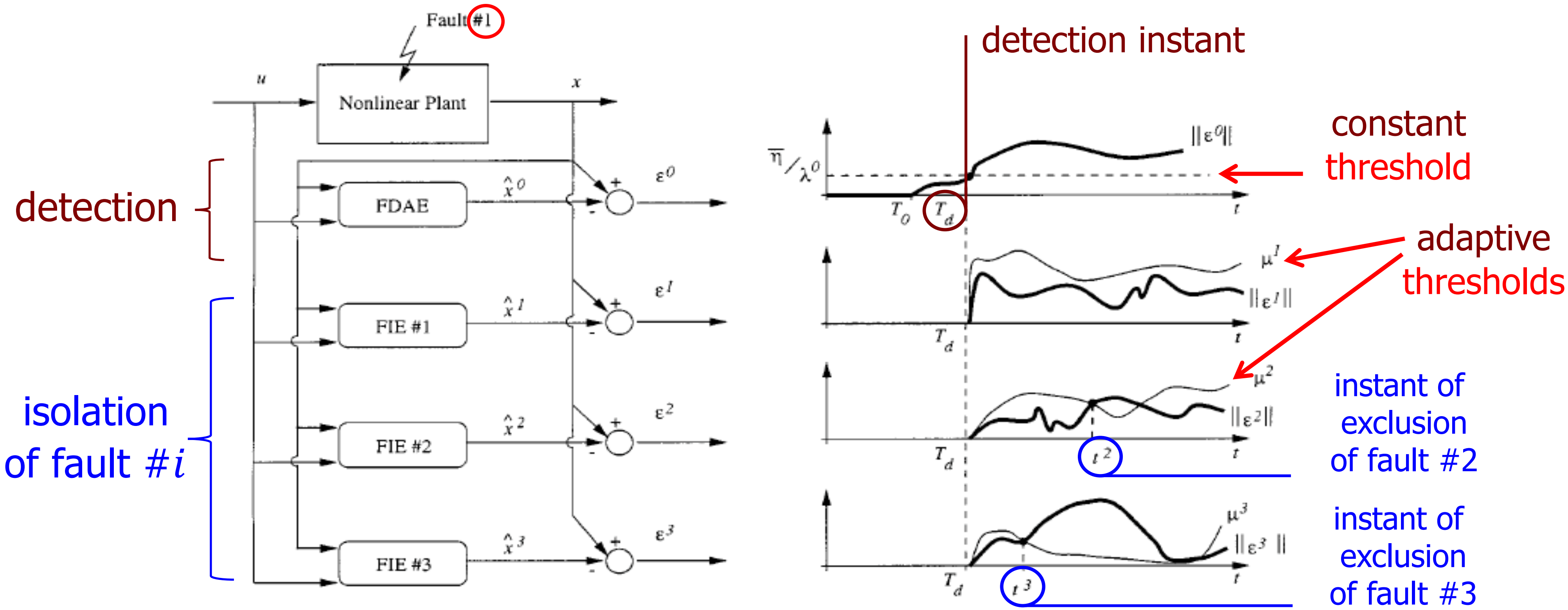
Typical FDI architecture

- 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

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) + F_V\dot{q} + F_S\,\mathrm{sgn}(\dot{q}) = \overbrace{u - u_f}$$

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 $u_{f,i} = b_i$ Ex: ??
- 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

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

$K > 0$ 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 $\tau_i = 1/k_i$

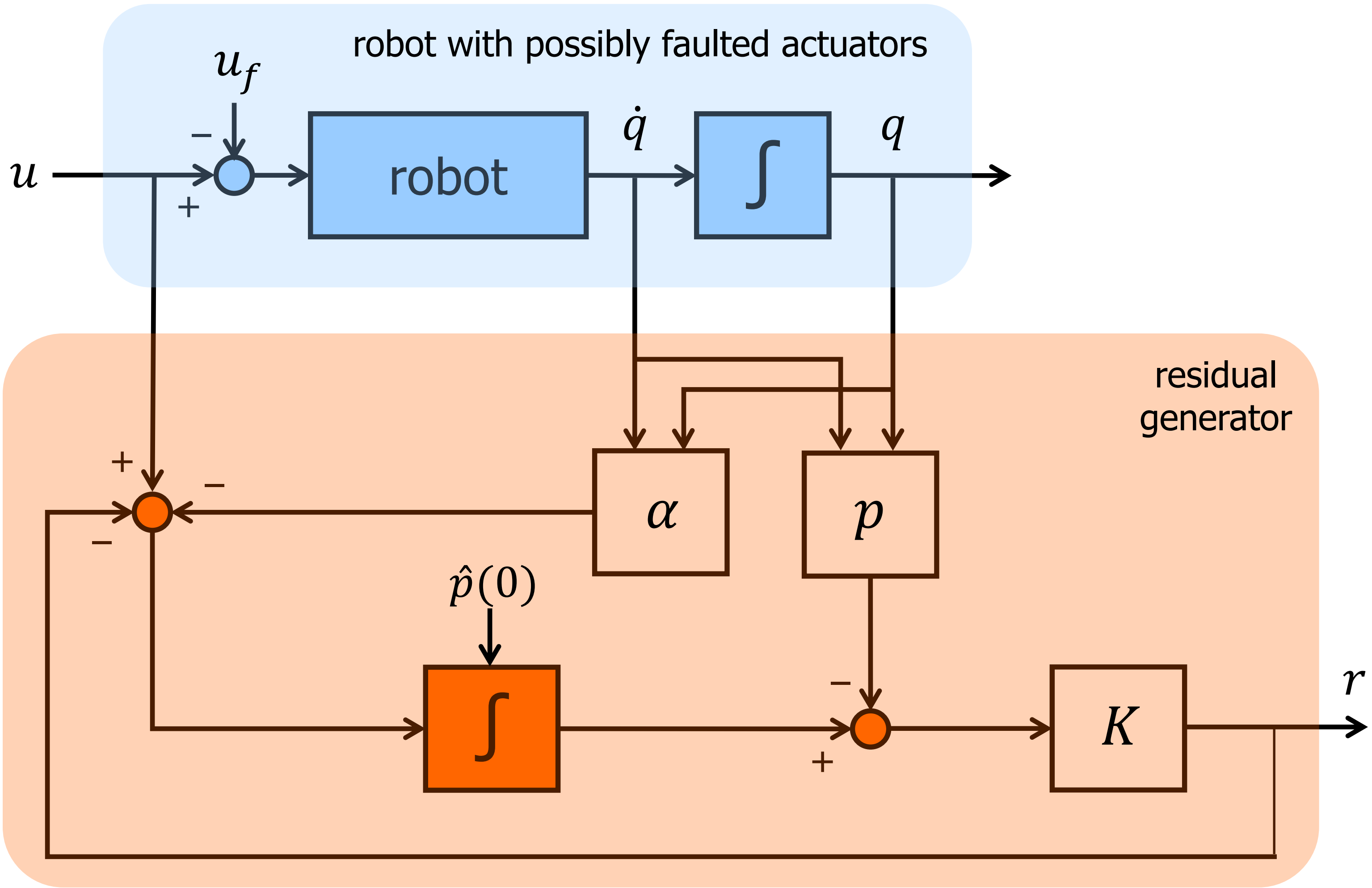
$$\boxed{\dot{r} = -Kr + Ku_f}$$

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...

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

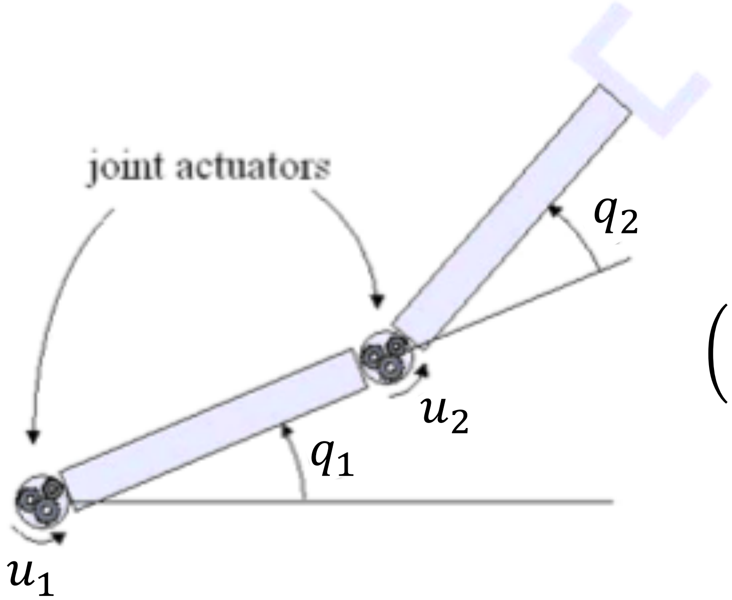
$\Updownarrow$

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

$$e_{obs} = u_f - r \quad \Rightarrow \quad \dot{e}_{obs} = \dot{u}_f - \dot{r} = \dot{u}_f - K\left(\dot{\hat{p}} - \dot{p}\right)$$
$$= \dot{u}_f - K\Big((u - \alpha - r) - (u - \alpha - u_f)\Big)$$
$$= \dot{u}_f - K(u_f - r) = \dot{u}_f - Ke_{obs} \cong -Ke_{obs}$$

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

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

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

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

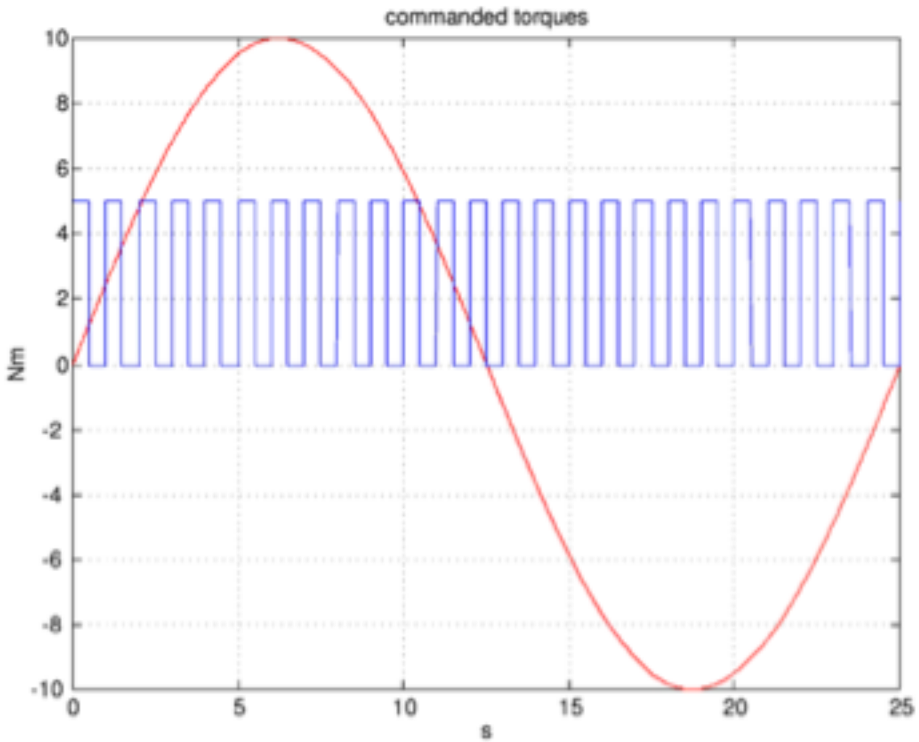
$$\alpha_2 = -\frac{1}{2}\dot{q}^T\frac{\partial M(q)}{\partial q_2}\dot{q} + g_2(q)$$

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

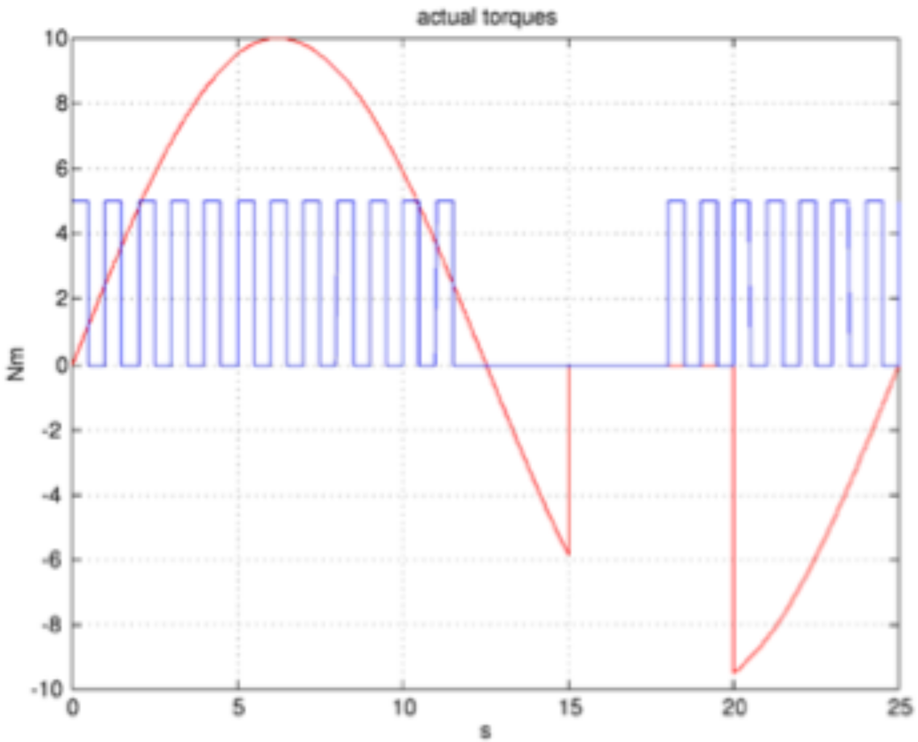
Faults on both actuators

(total, intermittent, concurrent)

commanded torques (in open loop)



actual (faulted) torques



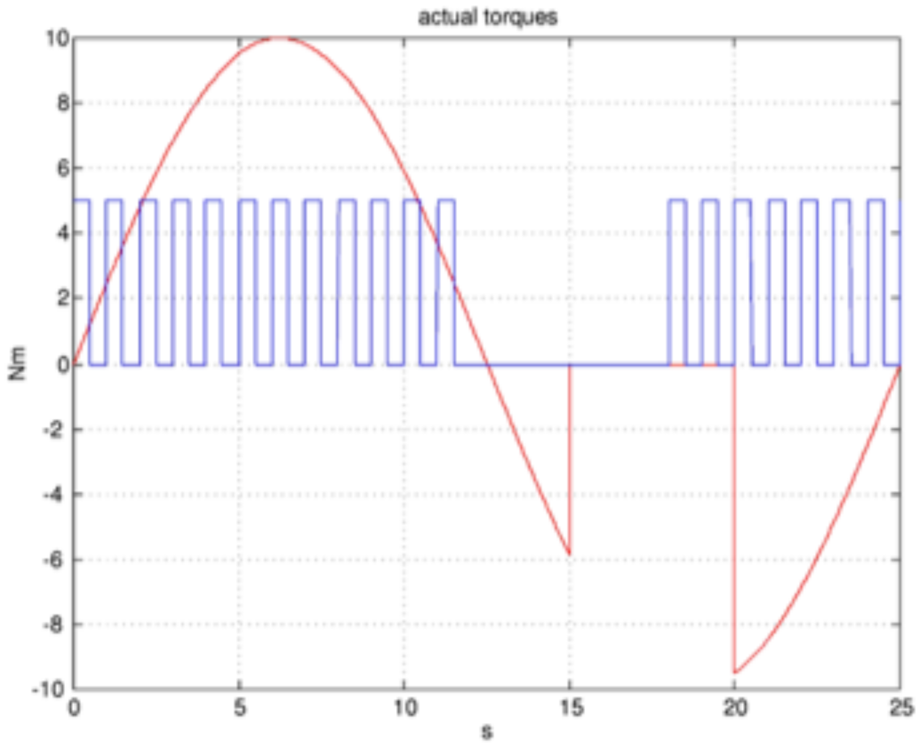
= first joint (fault for $t \in [15 \div 20]$ sec)

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

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

First simulation

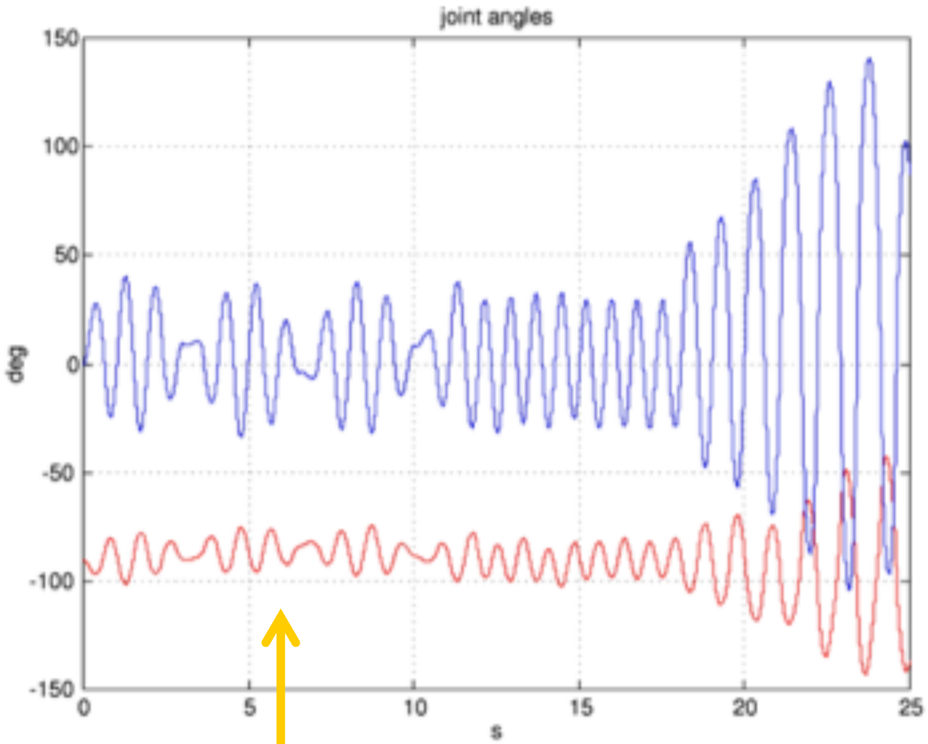
actual torques (to the robot)



= first joint

= second joint

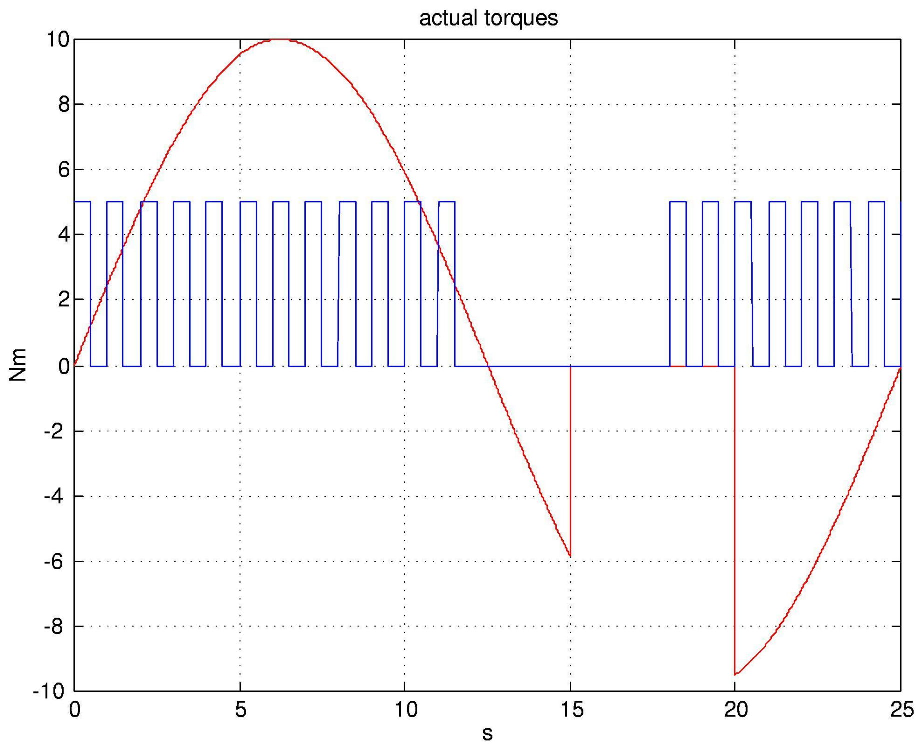
(measured) joint positions



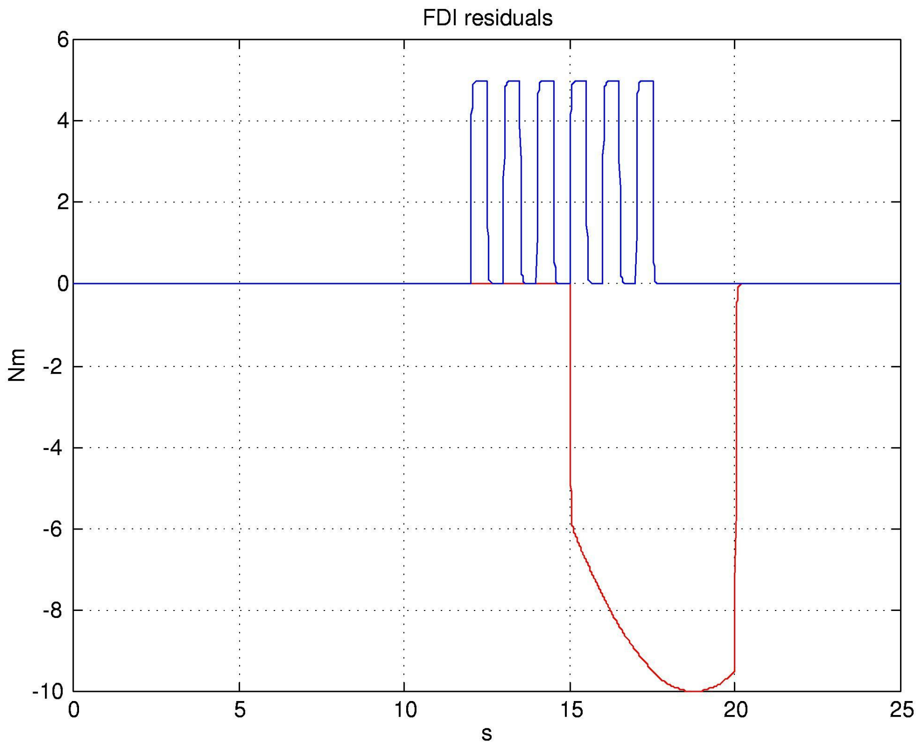
no clear evidence of faults in the dynamic evolution of the system!

First simulation – FDI

actual torques (to the robot)



residuals



= first joint

= second joint

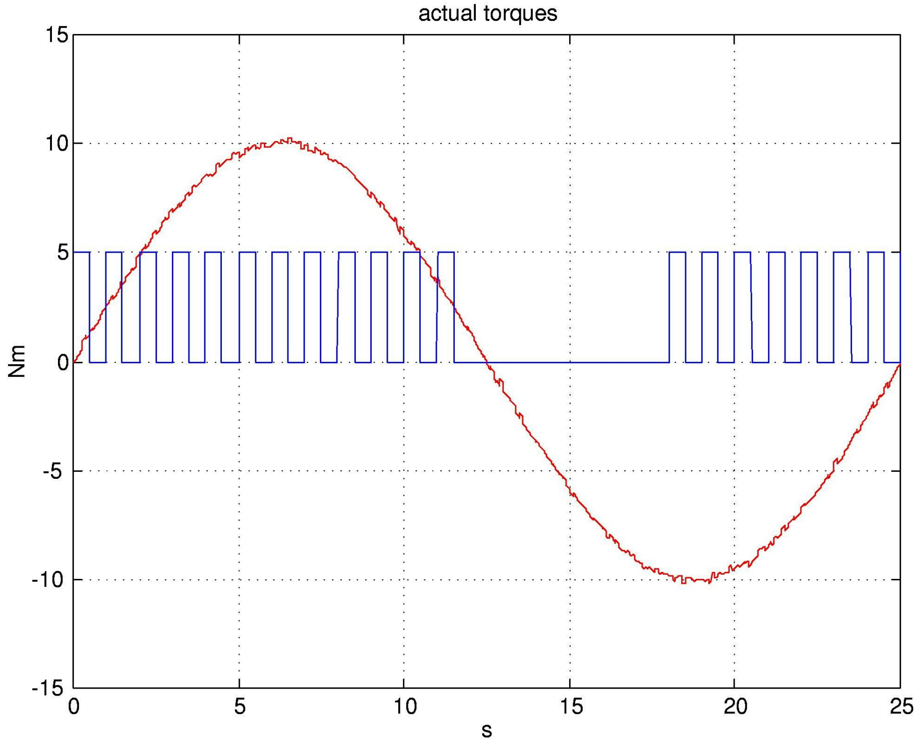
$$K = \mathrm{diag}\{50, 50\}$$

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

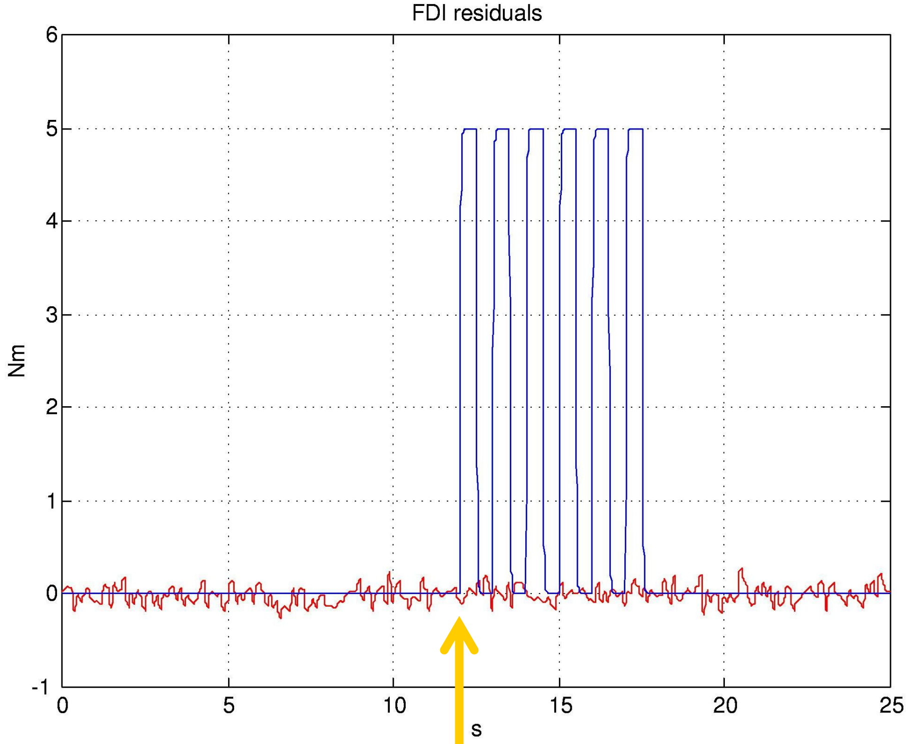
Second simulation – FDI

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

actual torques (to the robot)



residuals



red line = first joint

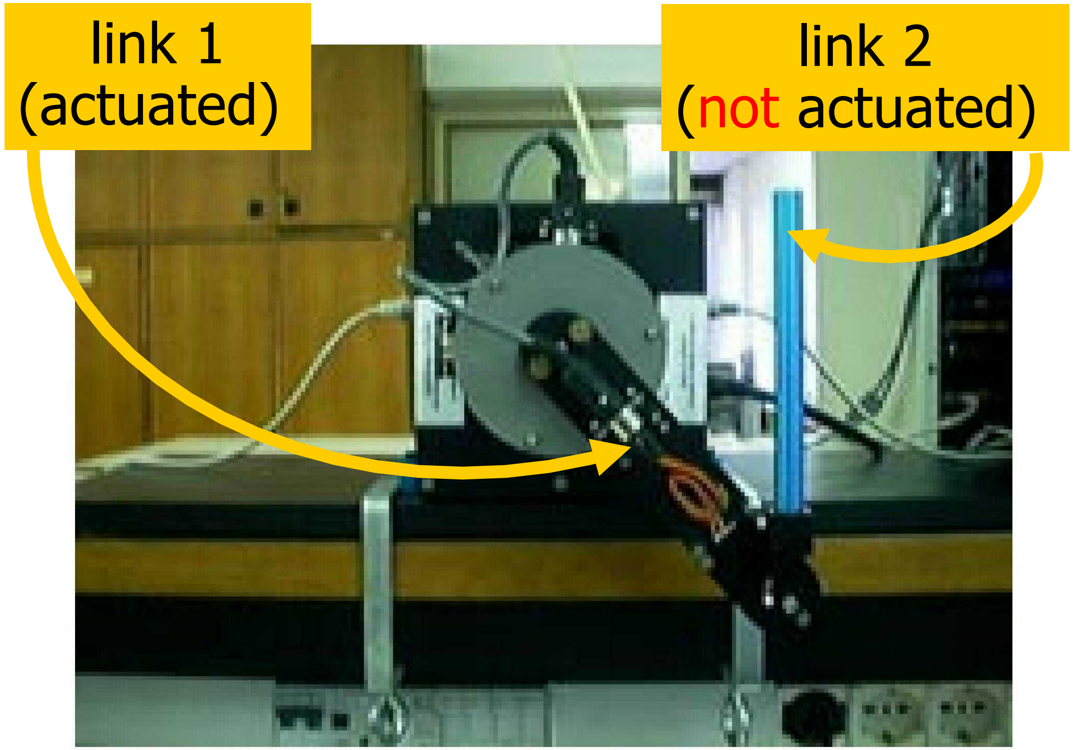
blue line = second joint (fault for $t \in [12 \div 18]$ sec)

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

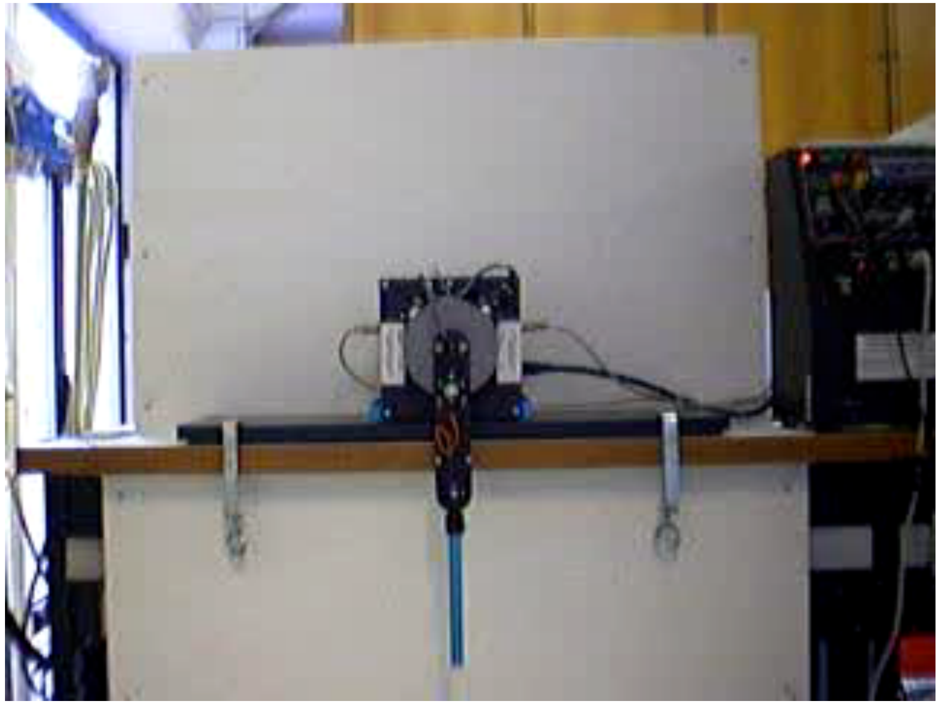
Experimental setup

Quanser Pendubot

video



with encoders on both joints



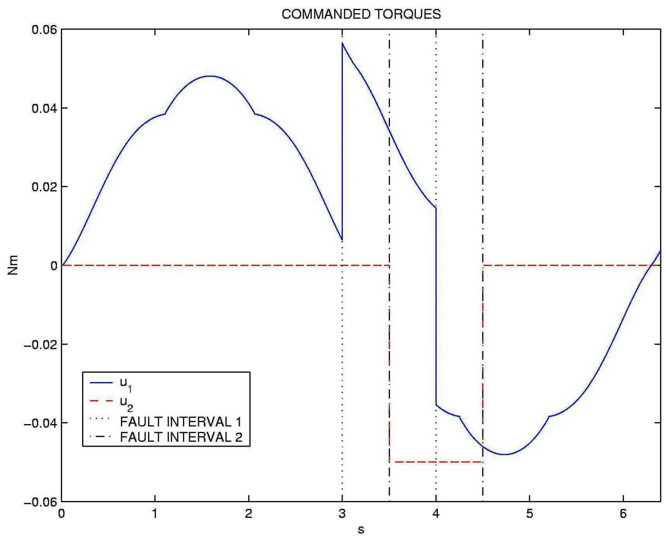
nonlinear control for swing-up

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

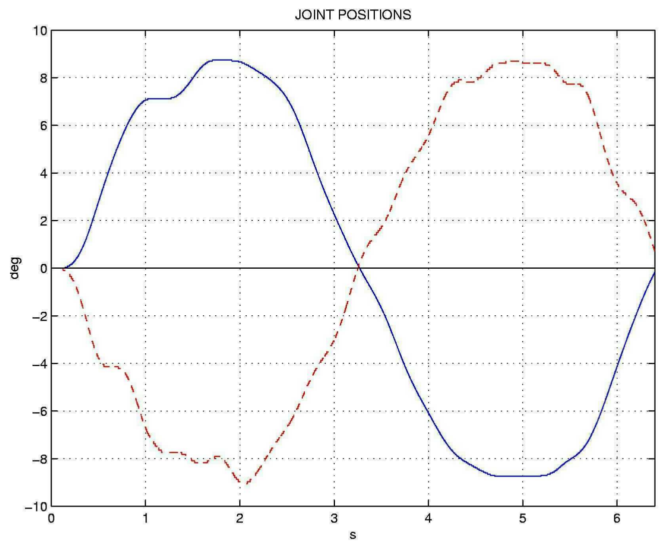
First experiment

- motor 1 driven by sinusoidal voltage of period 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

commanded torques



joint positions

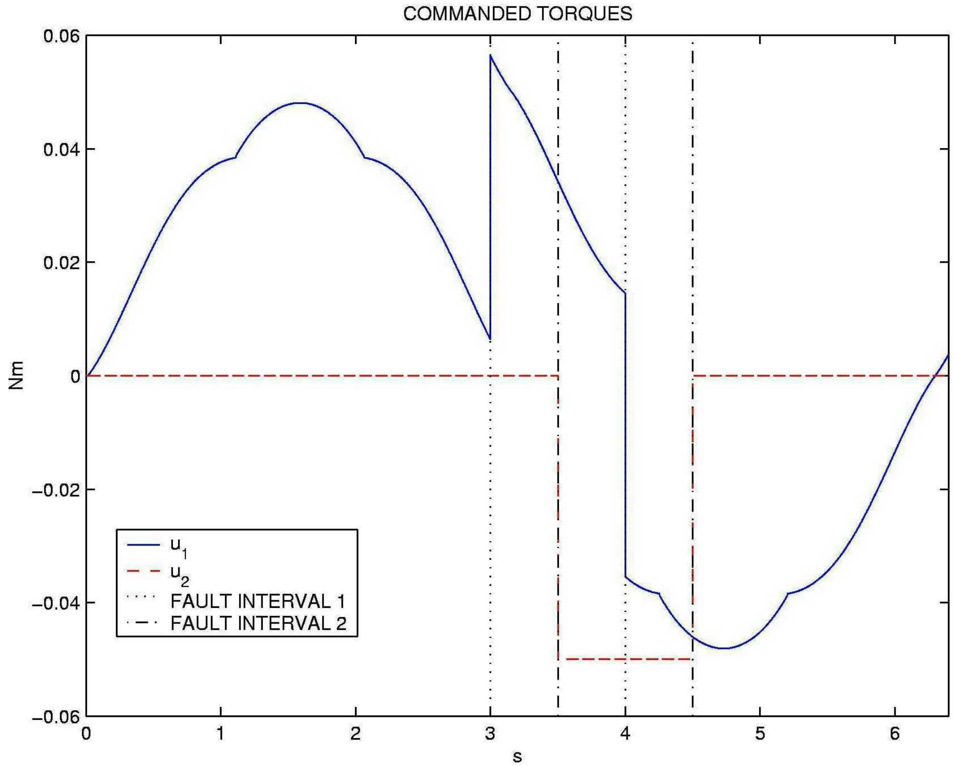


joint 1

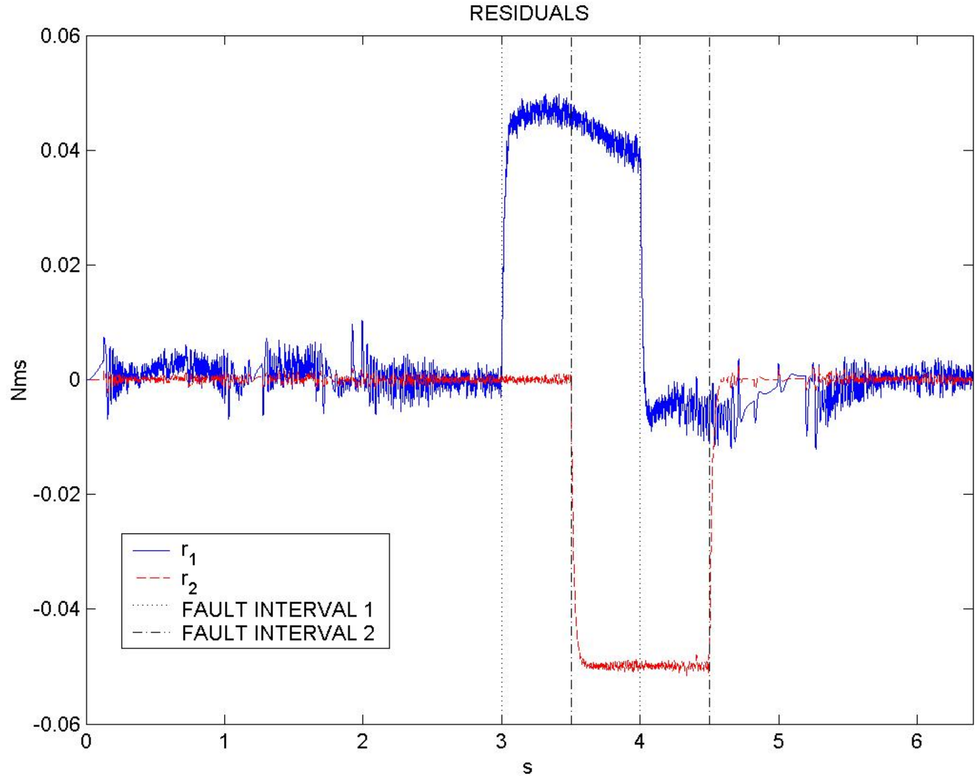
joint 2

First experiment – FDI

commanded torques



residuals

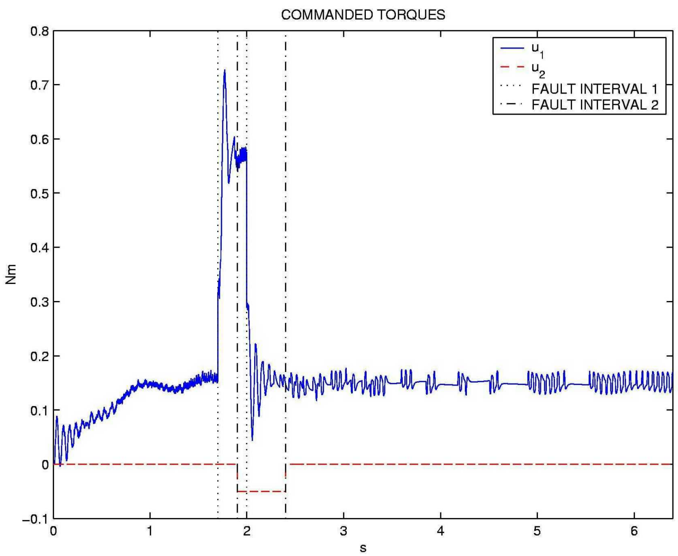


joint 1 joint 2

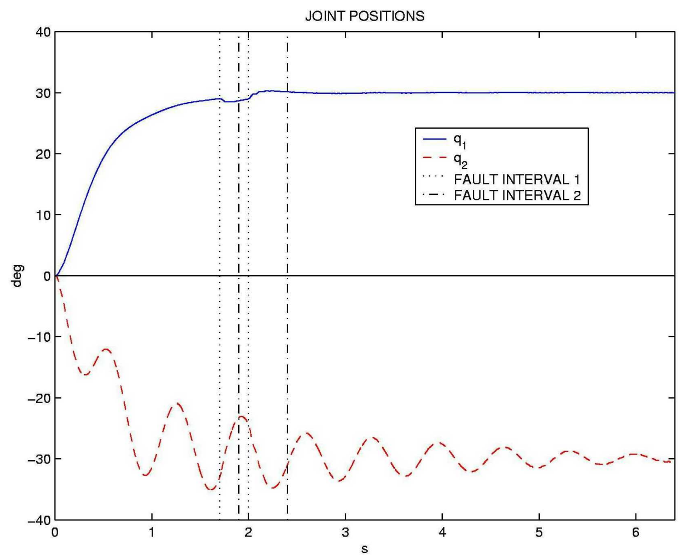
Second experiment

- 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

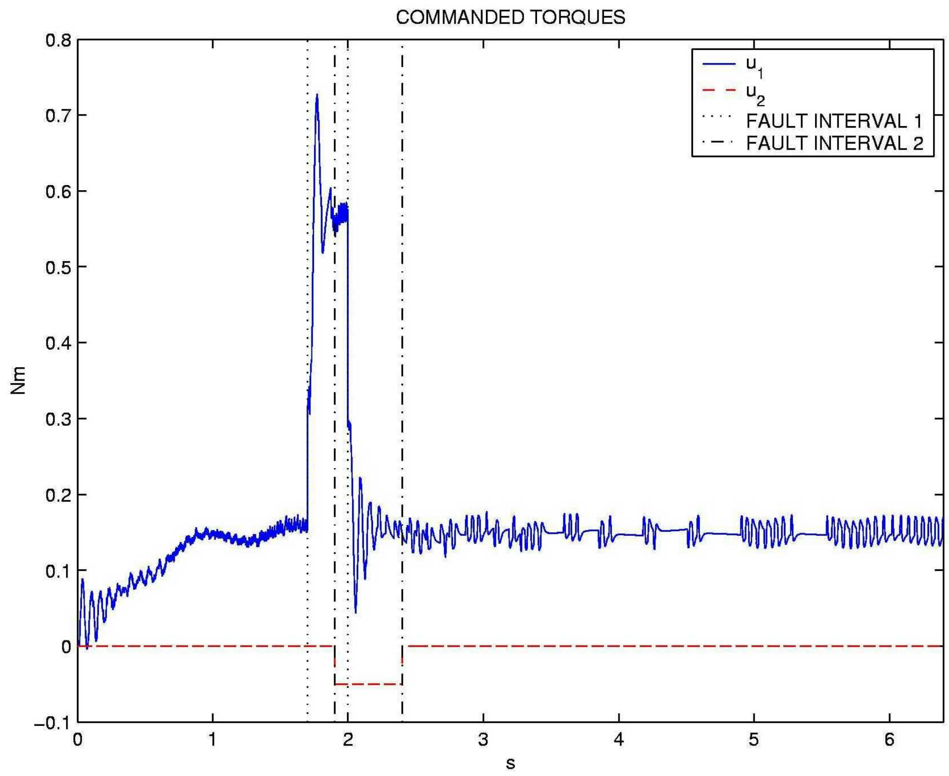


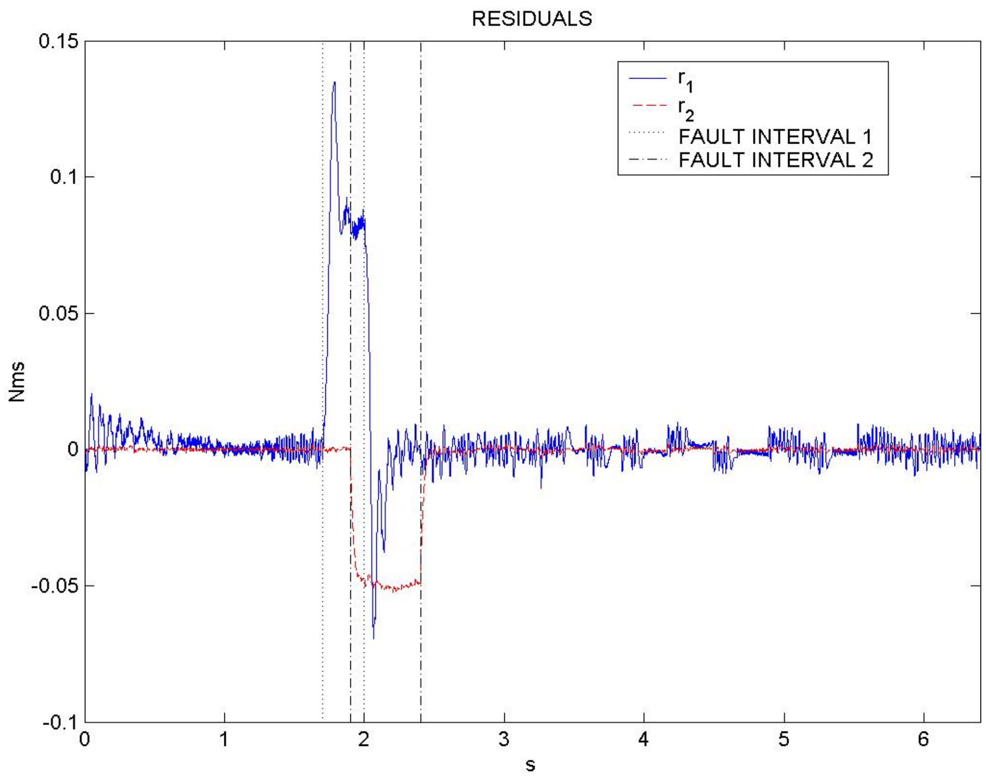
joint 1 joint 2

Second experiment – FDI

commanded torques

residuals





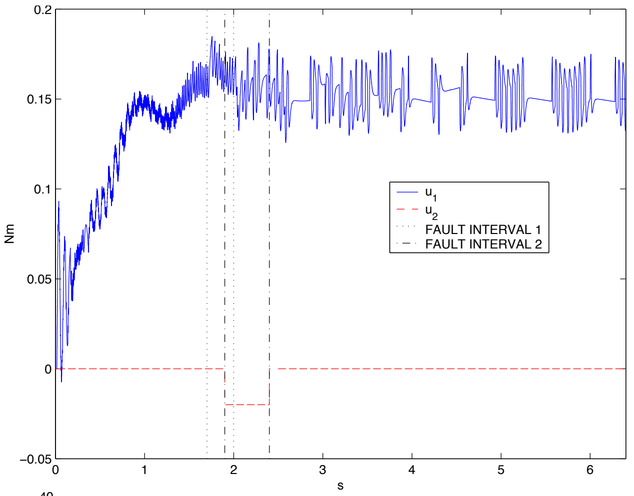
joint 1

joint 2

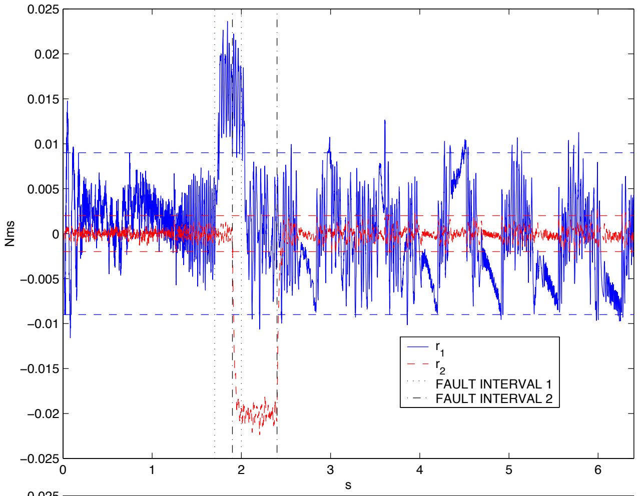
Third experiment – FDI

- 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



residuals

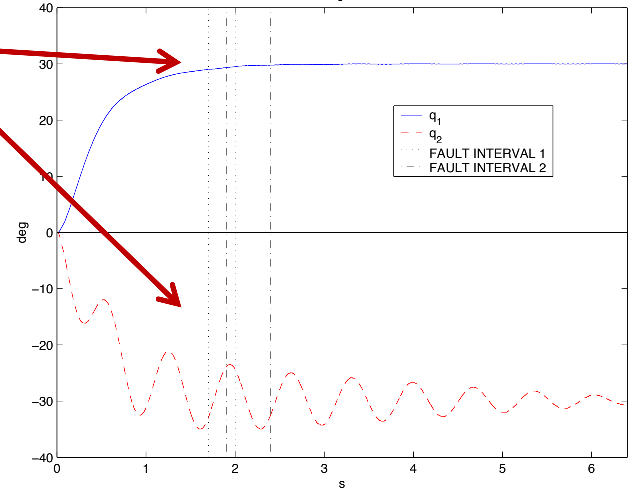


joint 1

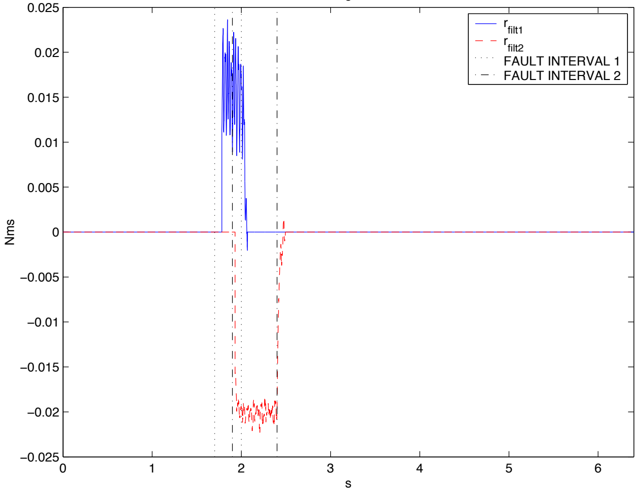
joint 2

faults are "unobservable" in these evolutions

joint positions



filtered residuals

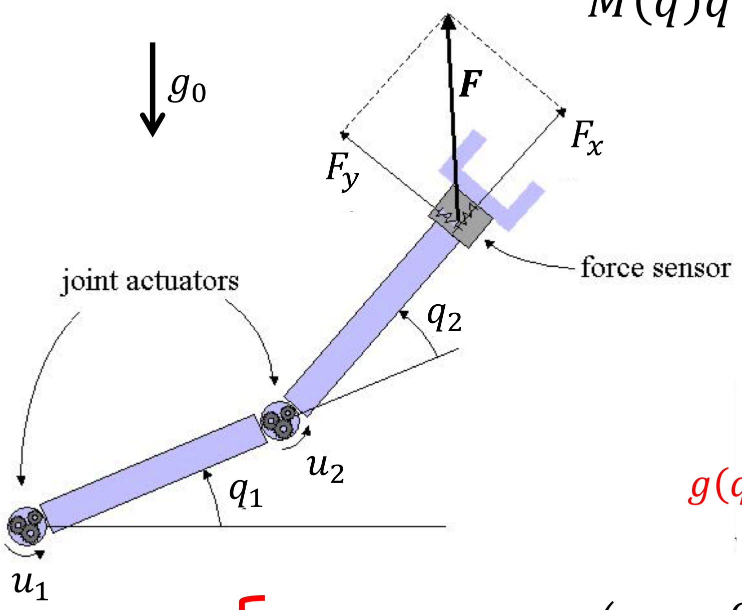


Extensions

- 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!

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

time derivative of transposed Jacobian adjoint

robot inertia

input torque

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

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

$\det J^T(q)$

measured force (nominal)

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

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

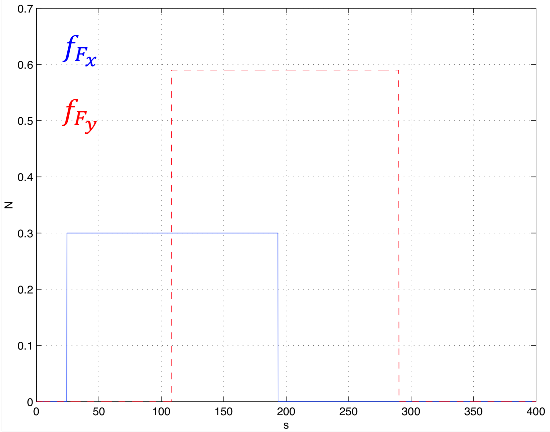
decoupled, though modulated by q_2

Ex: prove this expression!

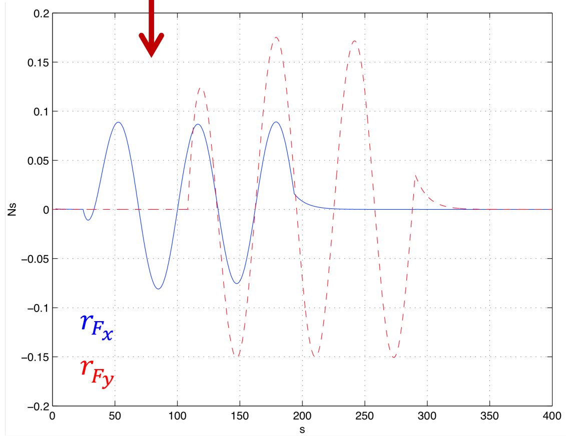
Isolation of F/T sensor faults

- simulation on the 2R robot

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 $t \in [109 \div 285]$



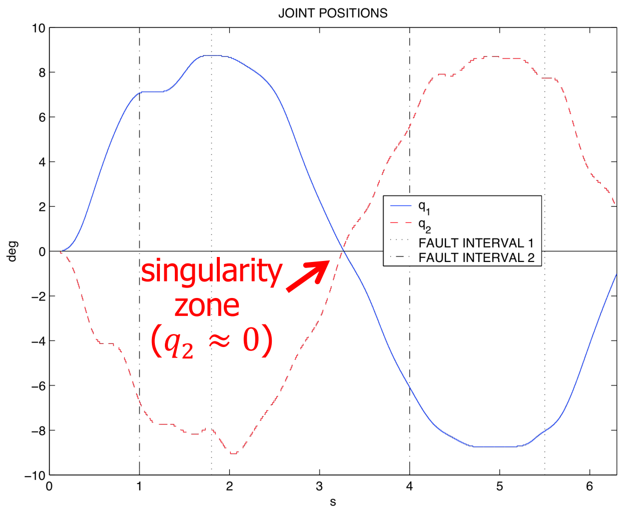
q_2 is tracking a sinusoid ($A = \pi/8$ rad, $\omega = 0.1$ rad/s)

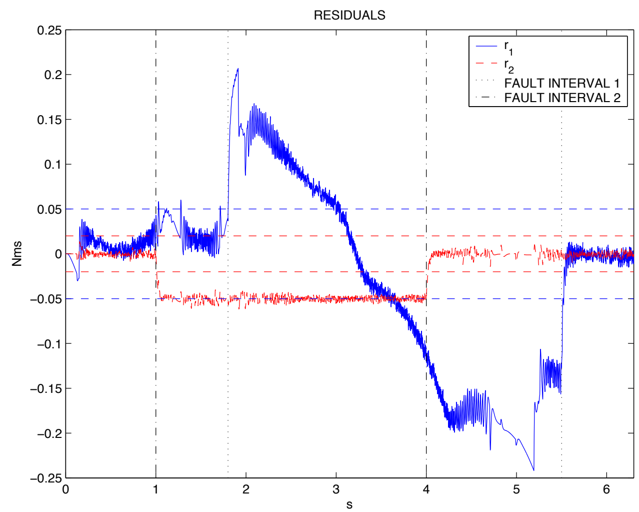


FDI residual
components
(with $K = 0.1I$)

- 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 $t \in [1 \div 4]$

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

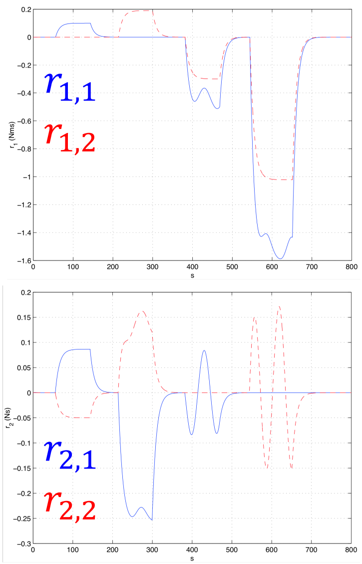
dependence of residuals on considered faults

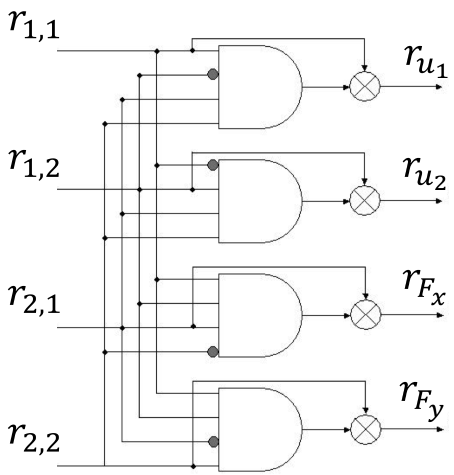
fault \ residual	$r_{1,1}$	$r_{1,2}$	$r_{2,1}$	$r_{2,2}$
f_{u_1}	1	0	1	1
f_{u_2}	0	1	1	1
f_{F_x}	1	1	1	0
f_{F_y}	1	1	0	1

isolation matrix

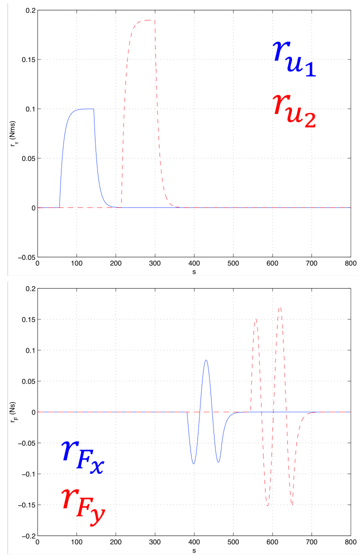
$r_{1,1}\ r_{1,2}$ \ $r_{2,1}\ r_{2,2}$	1 1	1 0	0 1	0 0
1 0	f_{u_1}	NA	NA	NA
0 1	f_{u_2}	NA	NA	NA
1 1	NC	f_{F_x}	f_{F_y}	NA
0 0	NA	NA	NA	no fault

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





isolation logics



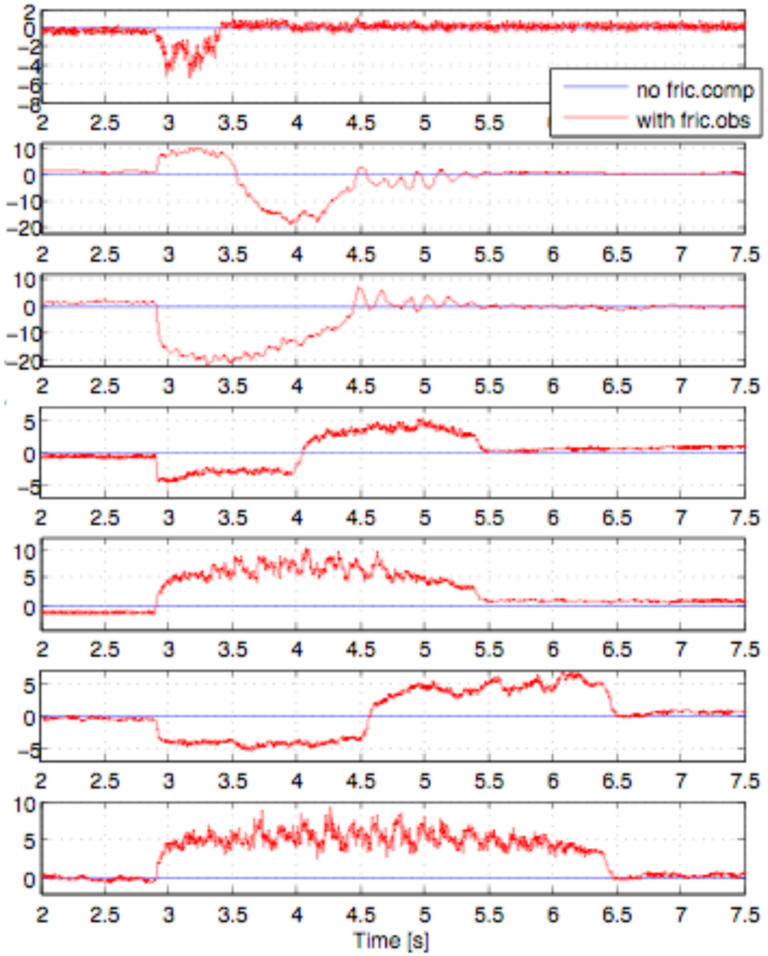
hybrid residuals allowing **isolation** of 4 faults

Experiments on friction compensation

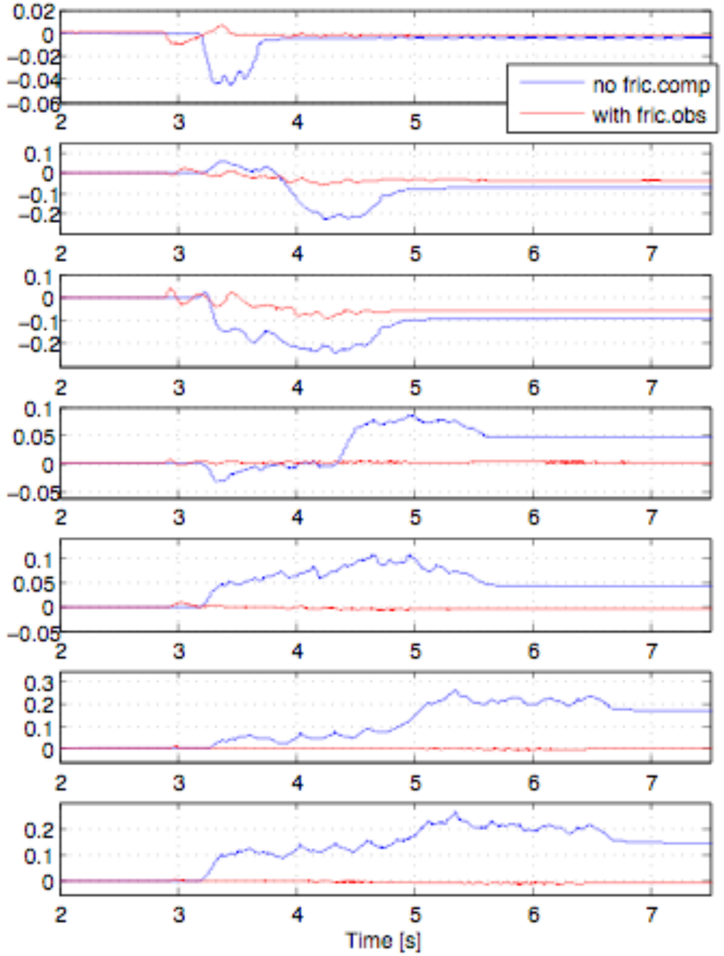
- results on the DLR 7R medical robot

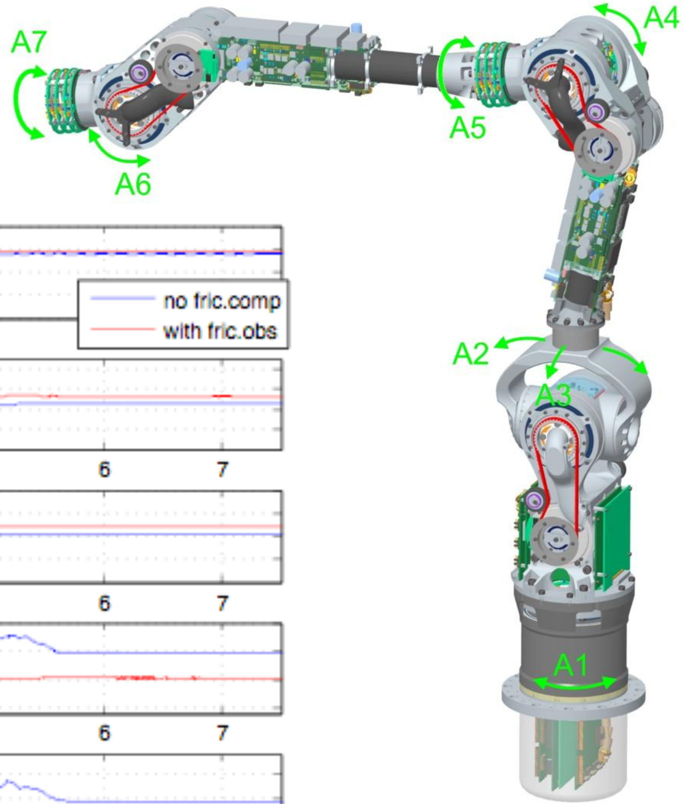
used then on-line
in control law...

friction estimate via residuals



position error



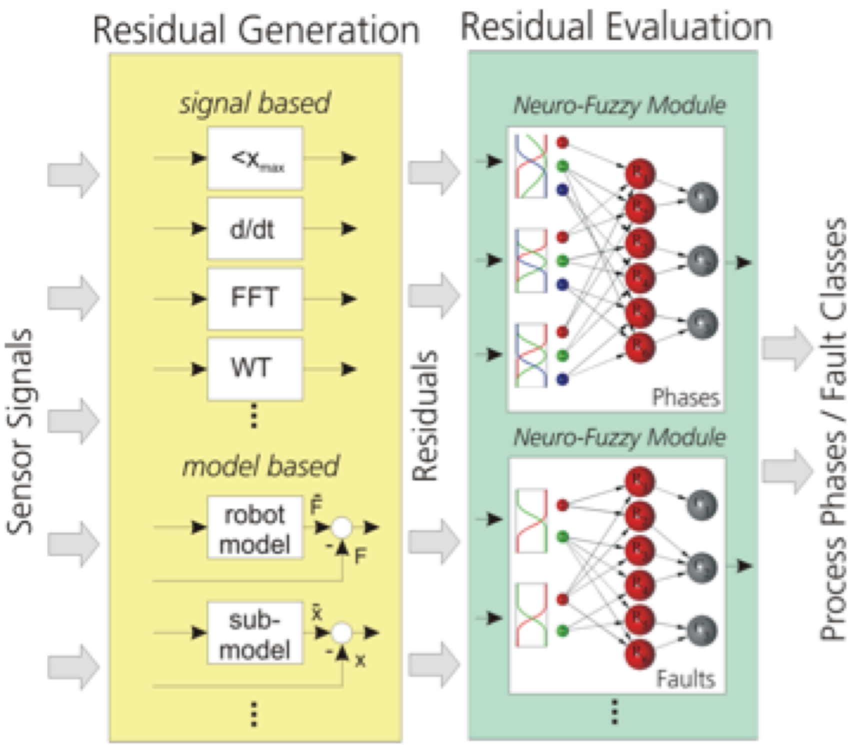


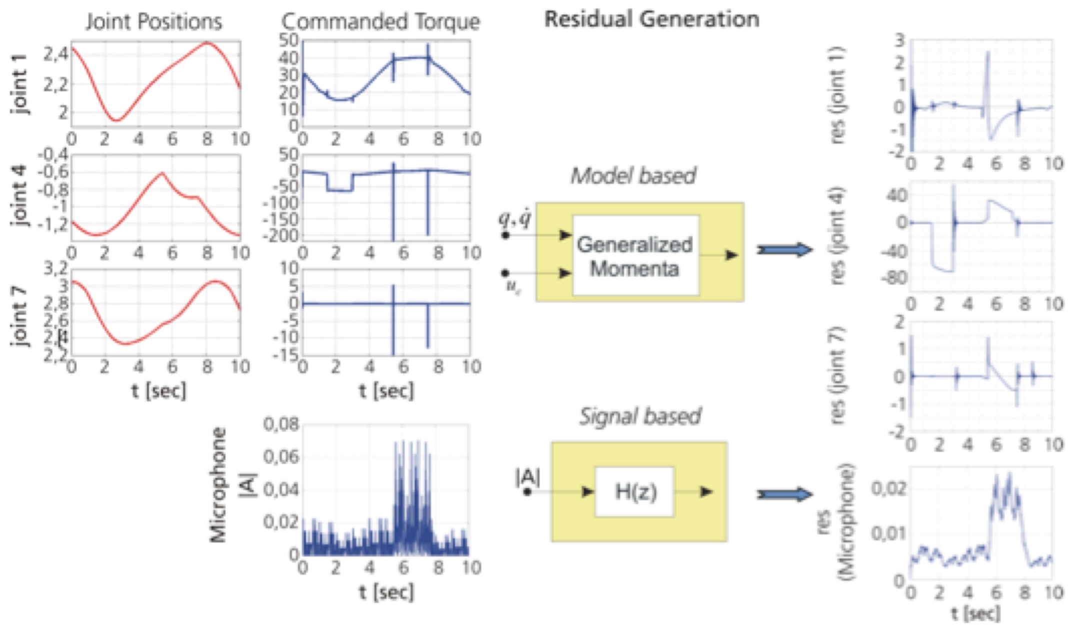
HD at the joints
⇒ elastic joint
dynamic model

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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