Robotics 2

Detection and isolation of robot actuator faults

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Fault diagnosis problems - 1

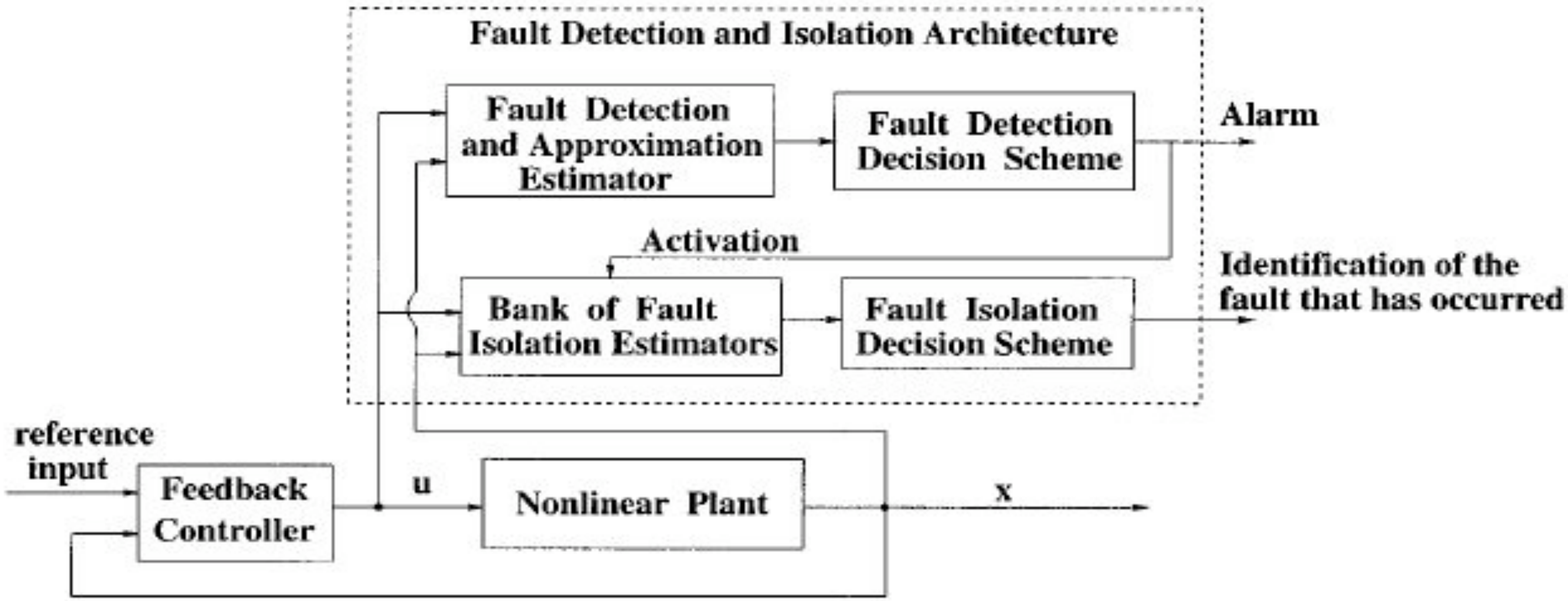
- in the diagnosis of faults possibly affecting a (nonlinear) dynamic system various problems can be formulated
- Fault Detection
  - recognize that the malfunctioning of the (controlled) system is due to the occurrence of a fault (or not proper behavior) affecting some physical or functional component 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 and from effects due to disturbances possibly acting on the system
- Fault Identification
  - determine the time profile 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 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)

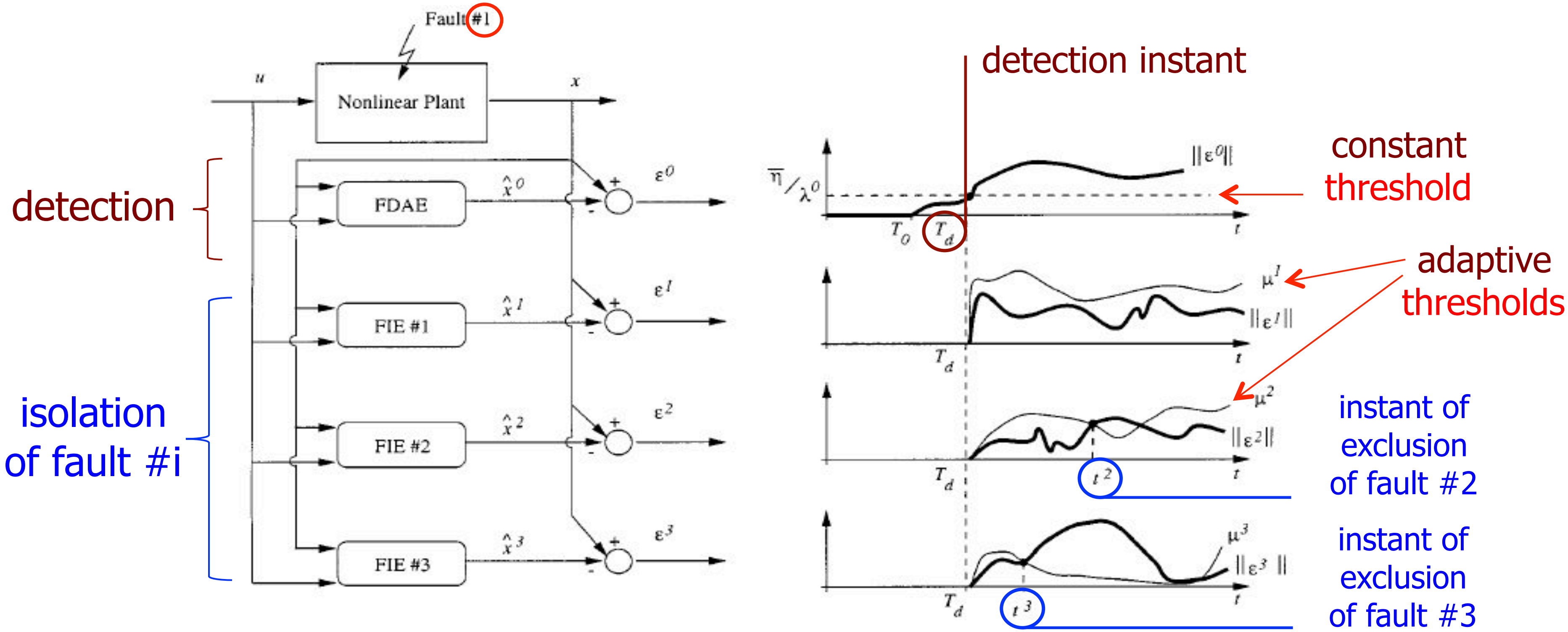
Typical FDI architecture

- 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

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) + F_v\dot{q} + F_s\,\mathrm{sign}(\dot{q}) = \underbrace{u - u_f}$$

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 $(u_{f,i} = \varepsilon u_i)$
- saturation $(u_{f,i} = u_i - u_{i,\max})$
- bias $(u_{f,i} = b_i)$
- block
- ... any type!

Working assumptions

- only the commanded input torque u is available
  - 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 moments

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

with associated dynamic equation

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

exploting the structure of centrifugal and Coriolis terms

decoupled components relative to the single fault inputs

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

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

FDI solution

- definition of a vector of residuals

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

$K > 0$
diagonal

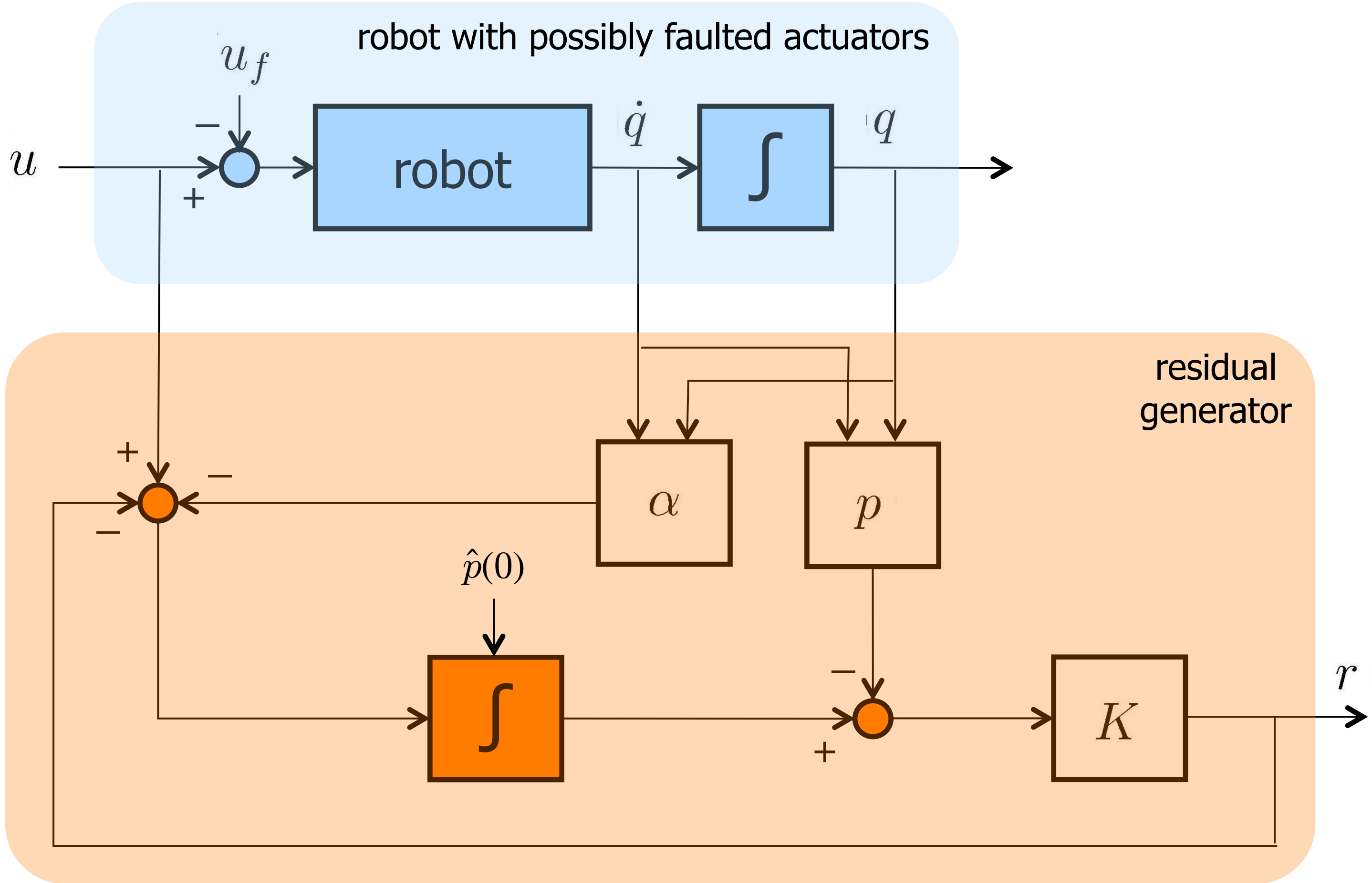
- no need of computing joint accelerations nor to invert the robot inertia matrix $M(q)$
- in ideal conditions of perfect model knowledge

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

N decoupled stable 1st order filters, with unitary gains

for sufficiently large K, r reproduces u_f

Block diagram of the residual generator



correct initialization $\hat{p}(0) = p(0)$

$$r = K\left[\int (u - \alpha - r)dt - p\right]$$

Residual generator as a "disturbance observer"

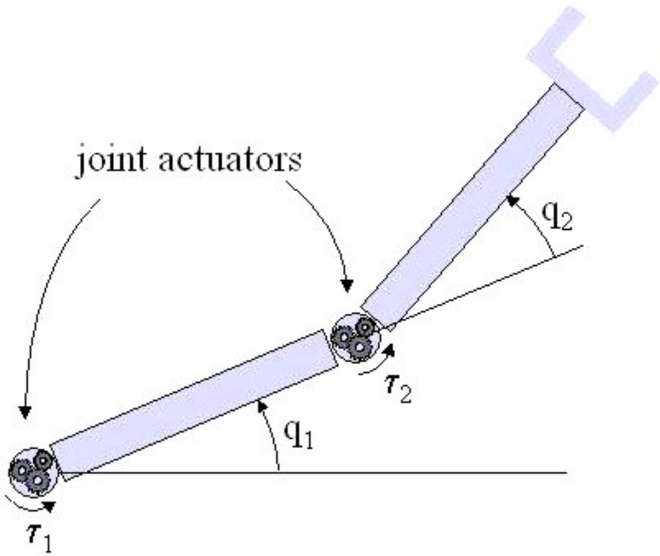
$$\begin{aligned}\dot{\hat{p}} &= u - \alpha(q,\dot{q}) + K(p - \hat{p})\\ r &= K(\hat{p} - p)\end{aligned}$$

$\Updownarrow$

dynamic observer of the unknown actuation faults
(= external disturbances)
with linear error dynamics

A worked-out example

- planar 2R robot under gravity



dynamic model (without friction)

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

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

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

computation of the residual vector

$$r = K\left[\int (u - \alpha - r)dt - p\right]$$

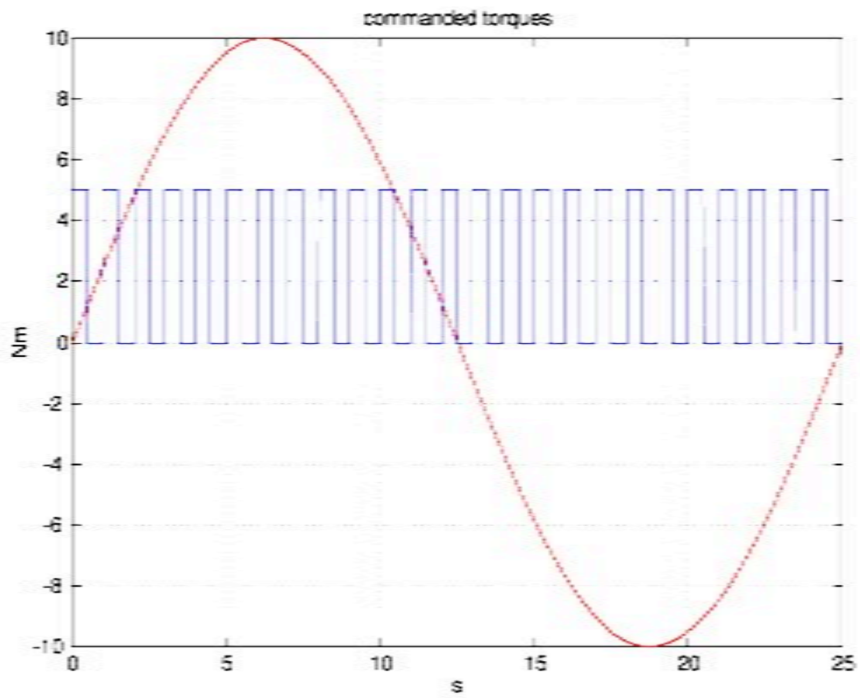
$$p = M(q)\dot{q}$$

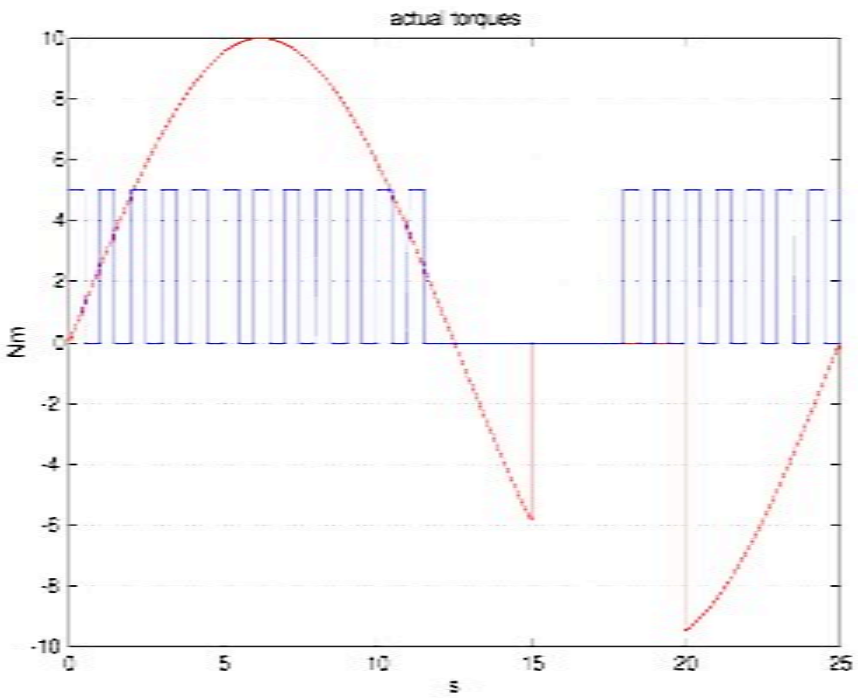
$$\begin{aligned} \alpha_1 &= g_1(q) = a_4c_1 + a_5c_{12} \\ \alpha_2 &= -\frac{1}{2}\dot{q}^T \frac{\partial M(q)}{\partial q_2}\dot{q} + g_2(q) \\ &= a_2\dot{q}_1(\dot{q}_1 + \dot{q}_2)s_2 + a_5c_{12} \end{aligned}$$

Faults on both actuators
(total, intermittent, concurrent)

commanded torques

actual (faulted) torques





= first joint

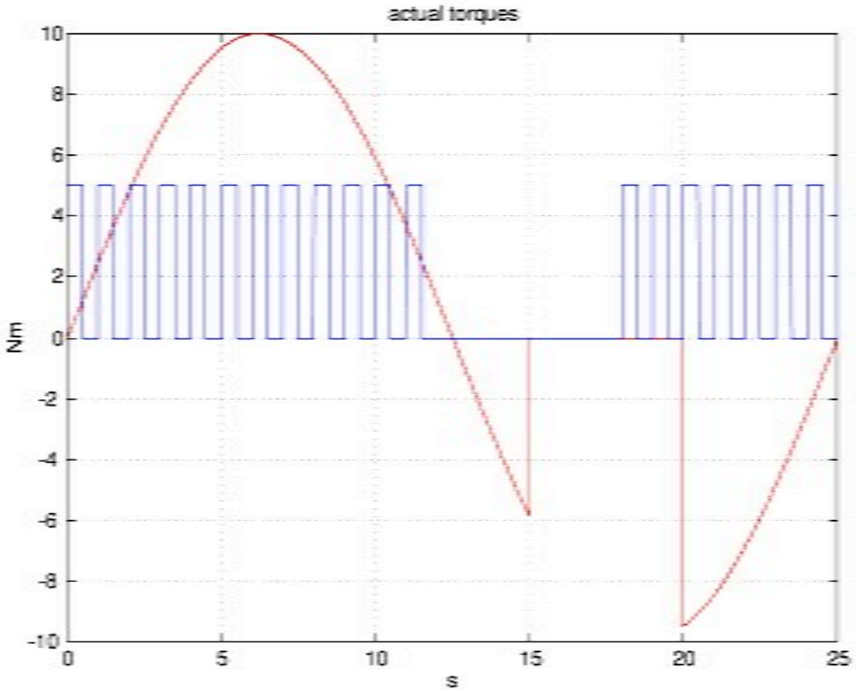
= second joint

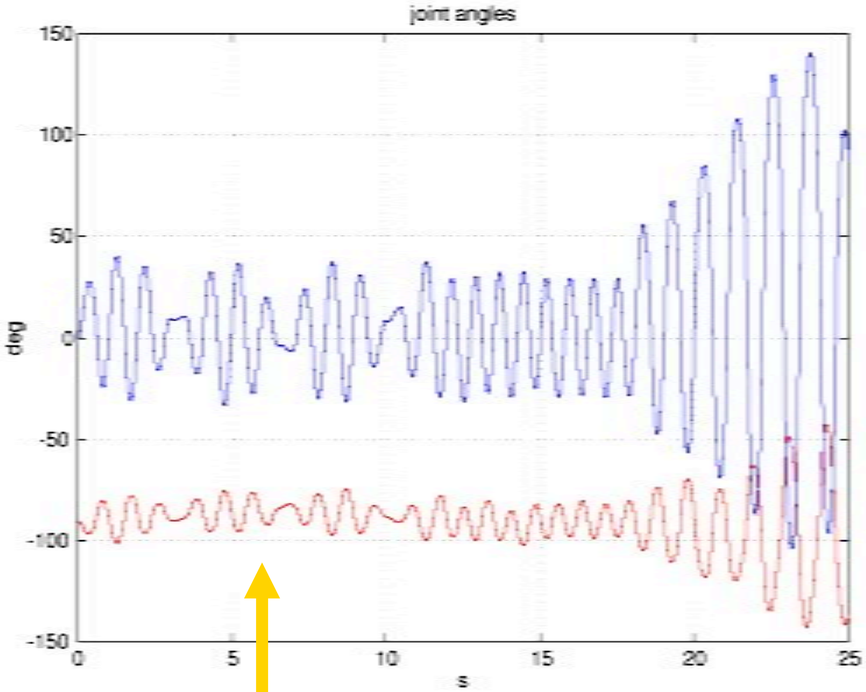
time interval of
fault concurrence

Simulation – 1

actual torques

(measured) joint positions





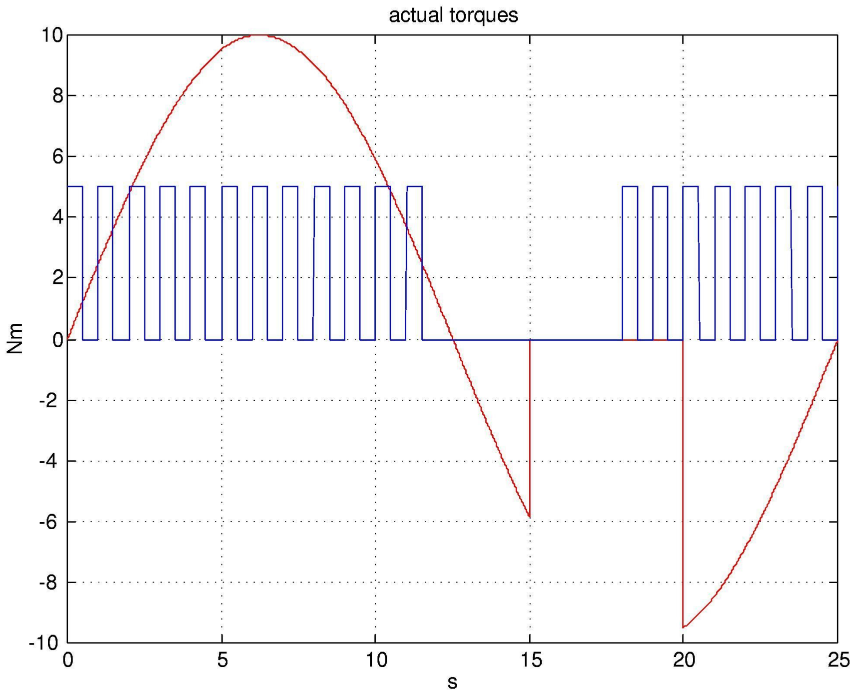
——— = first joint

——— = second joint

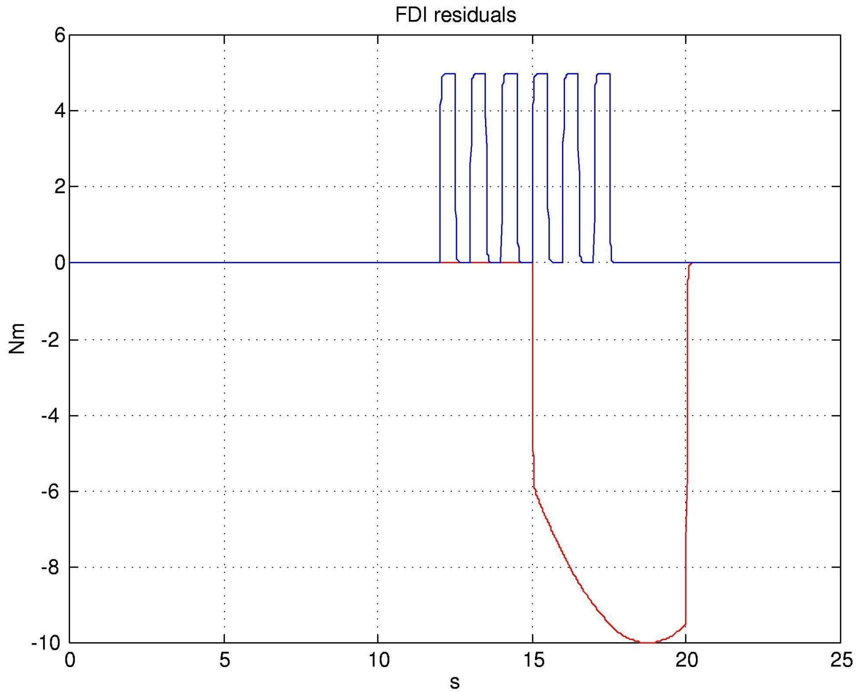
no clear evidence of the faults in the dynamic evolution of the system!

Simulation – 2

actual torques



residuals



= first joint

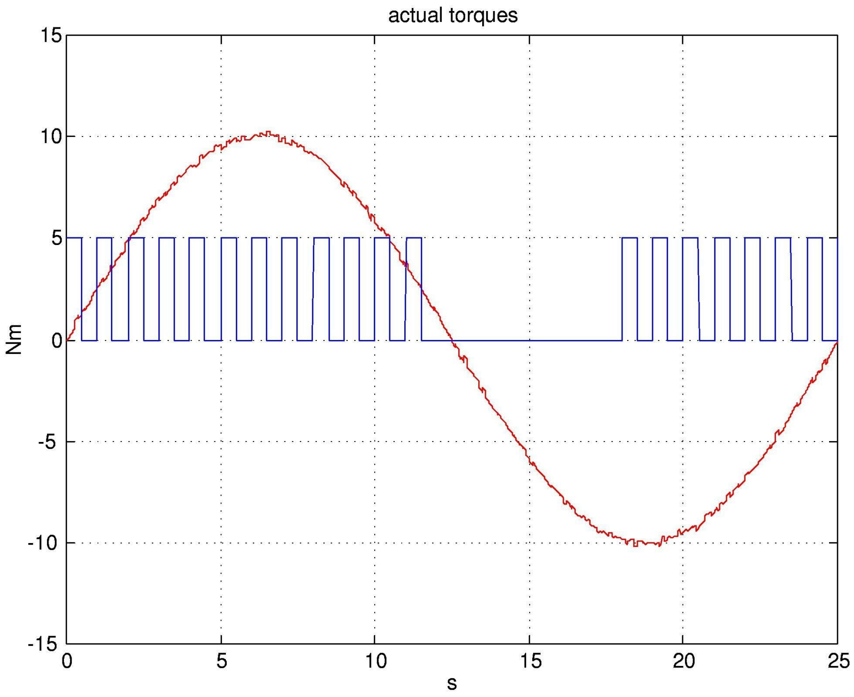
= second joint

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

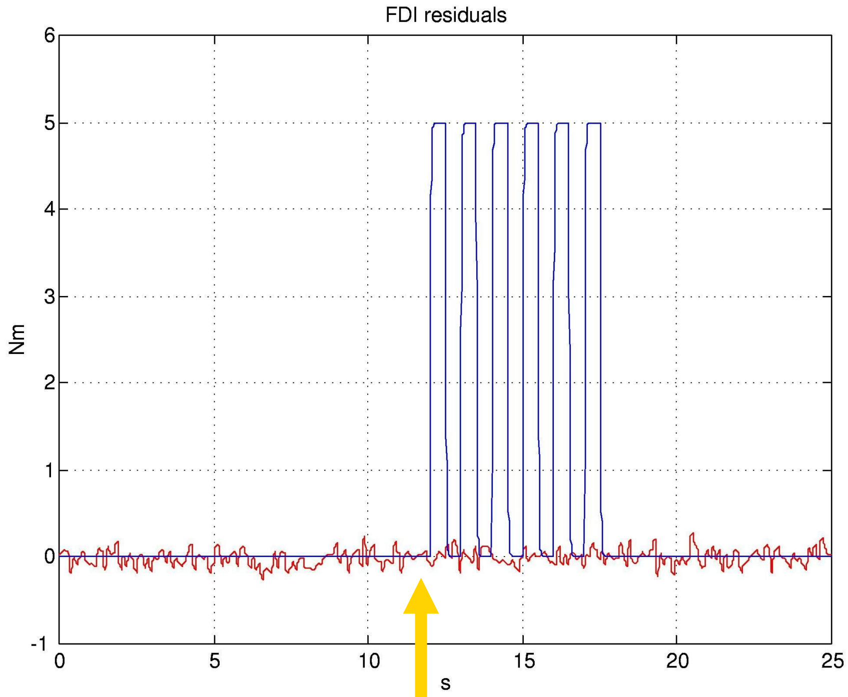
residuals reconstruct the "missing" part of the torques!

Simulation – 3
(total fault on second actuator, added noise on first channel)

actual torques



residuals



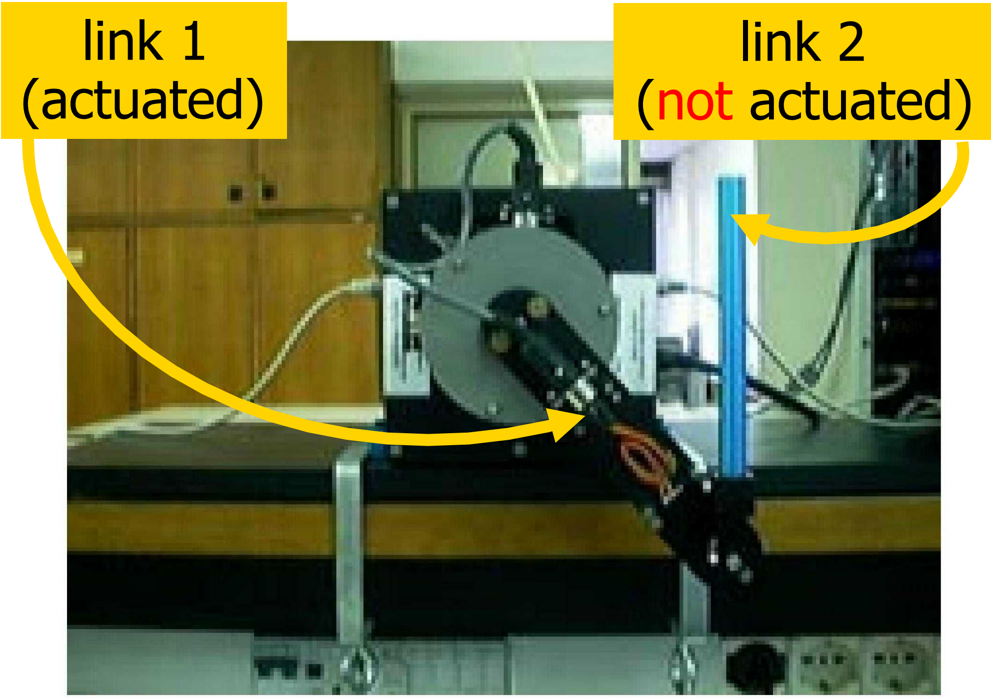
= first joint

= second joint

residual r_1 is not affected by the fault of the second motor, while residual r_2 is not affected by the disturbance on the first channel (decoupling properties)

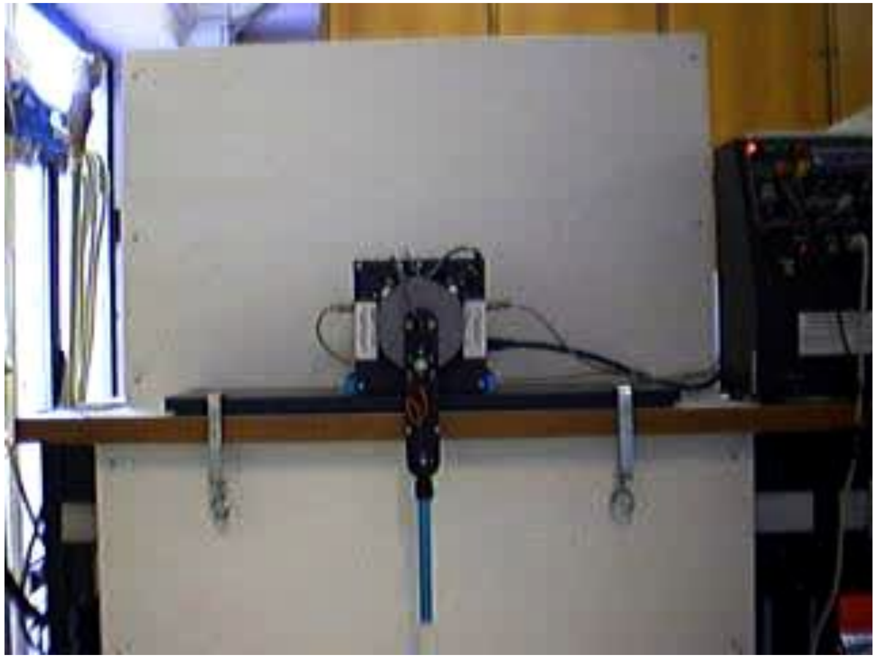
Experimental setup

Quanser Pendubot



with encoders on both joints

video



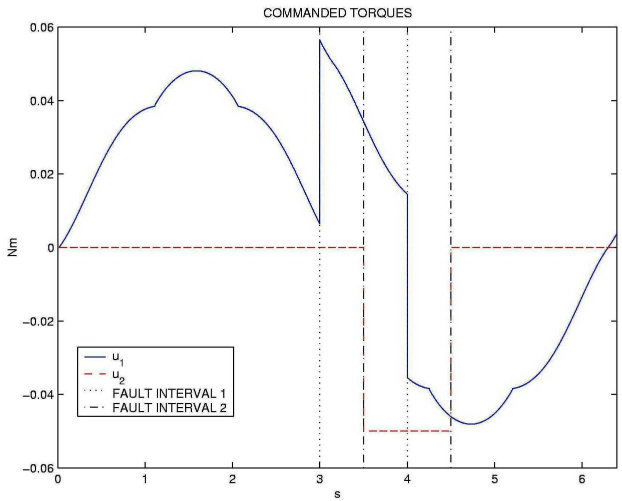
nonlinear control for swing-up

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

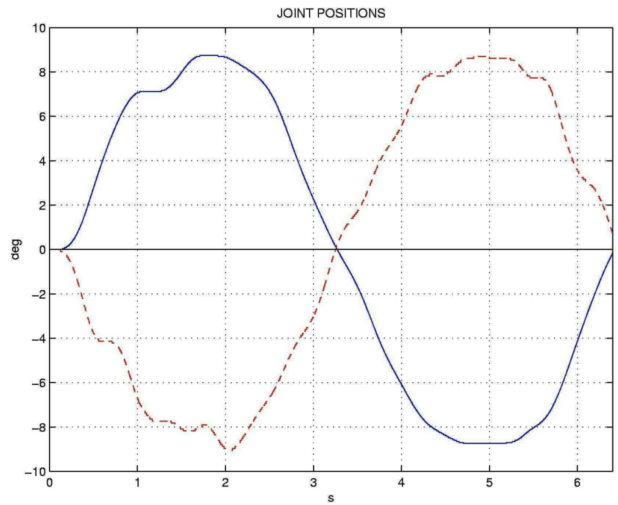
Experiment 1

- motor 1 driven by a 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 by the user, but the motor is not there …)
- fault concurrency for $t \in [3.5 \div 4]$ sec

commanded torques



joint positions

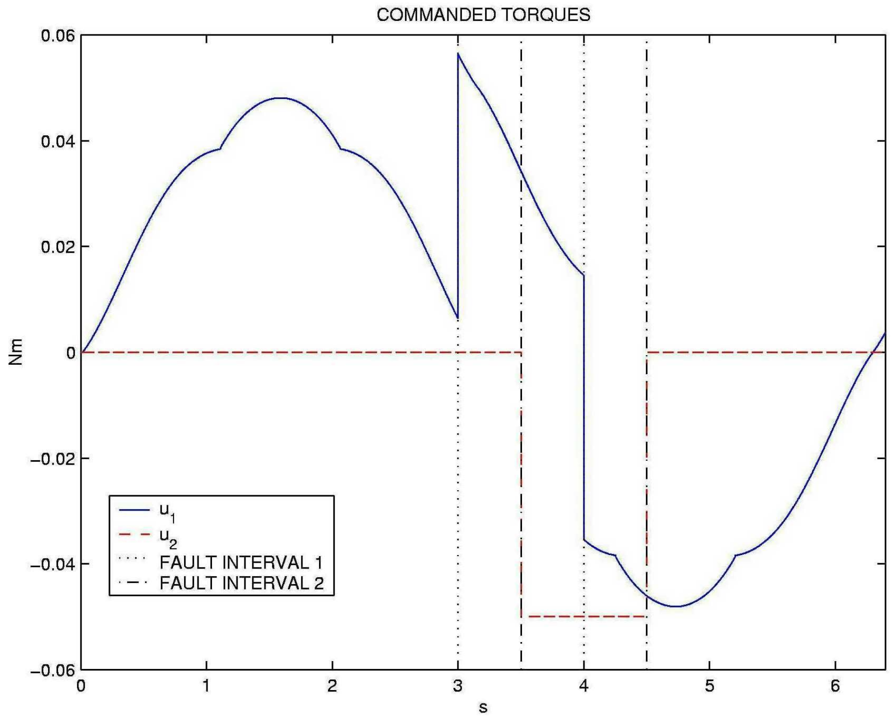


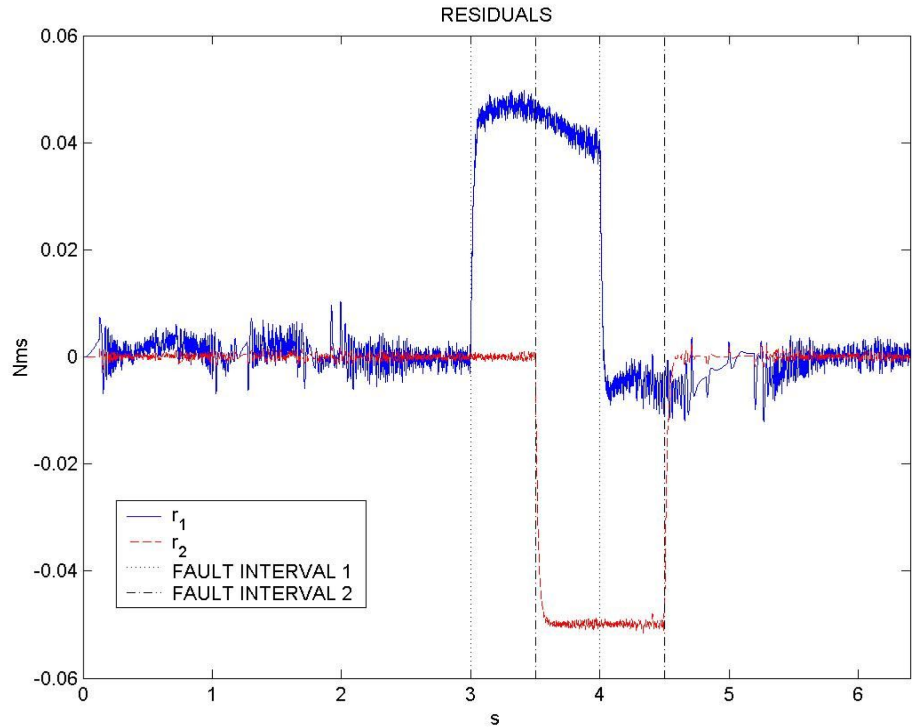
joint 1 joint 2

Experiment 1 - FDI

commanded torques

residuals



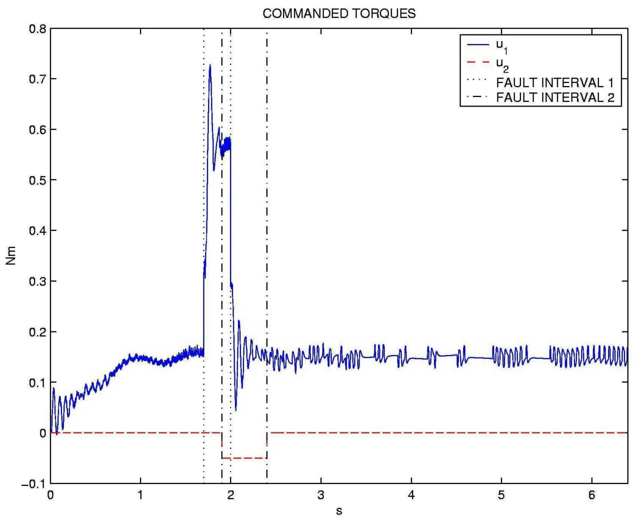


joint 1 joint 2

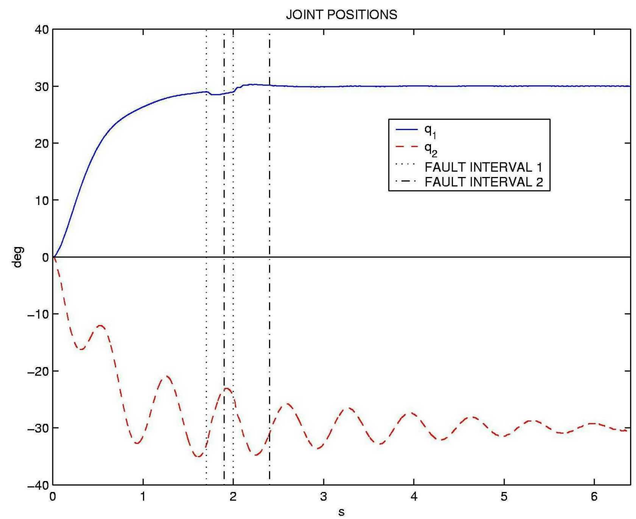
Experiment 2

- position regulation of the first joint at $q_{d1} = 30°$ (PID control)
- 50% power loss on motor 1 for t ∈ [1.7÷2] sec
- total fault on joint 2 for t ∈ [1.9÷2.4] sec (as before)
- fault concurrency for t ∈ [1.7÷1.9] sec

commanded torques



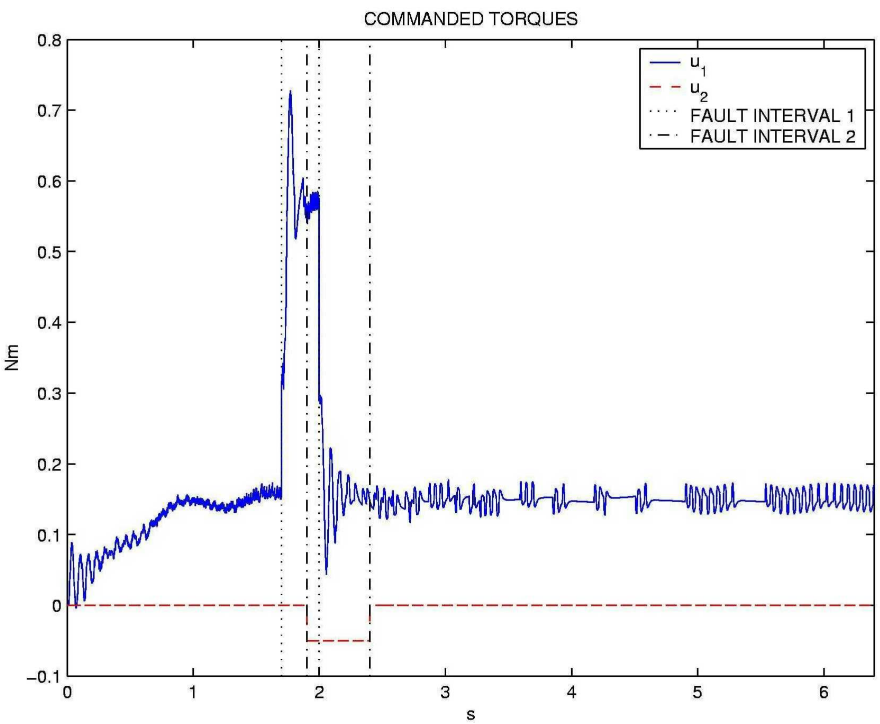
joint positions



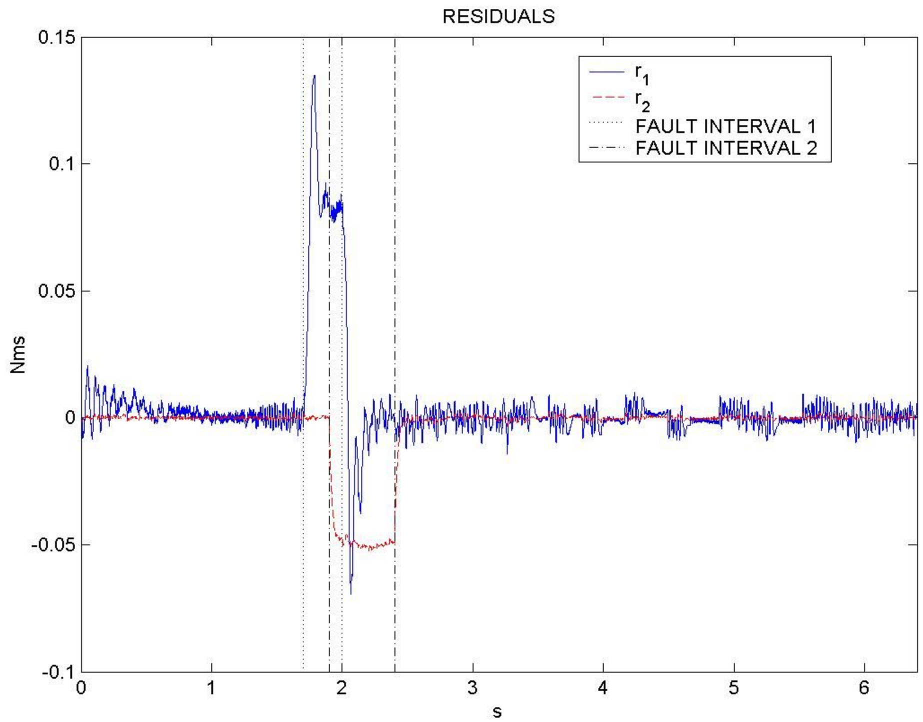
joint 1 — — joint 2

Experiment 2 - FDI

commanded torques



residuals



joint 1

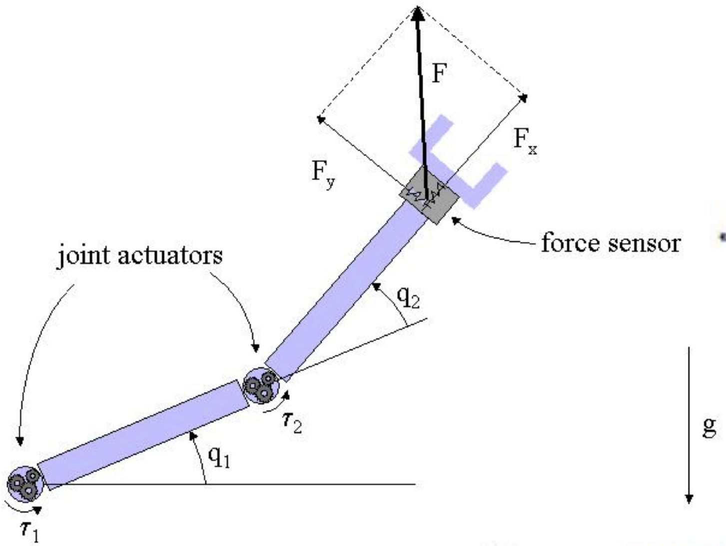
joint 2

Extensions

- the FDI method based on generalized momentum is easily extended to 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 the wrist force/torque sensor)
  - applies to all faults that instantaneously affect robot acceleration or torque (i.e., occurring at this same differential level)
- assuming non-concurrency (at most a single fault occurs at the same time) for a 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 force sensor mounted on the end-effector



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

robot Jacobian (expressed in end-effector frame)

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

adjoint of the Jacobian (singularity robust!)

time derivative of transposed Jacobian adjoint

robot inertia

measured force (nominal)

residual generator

$$\left\{\begin{aligned} \dot{\zeta} &= -J^{\mathsf{T}\,ad}(q) \begin{bmatrix} a_4 c_1 + a_5 c_{12} \\ a_5 c_{12} + a_2 s_2 (\dot{q}_1^2 + \dot{q}_1 \dot{q}_2) \end{bmatrix} + \begin{bmatrix} 0 & \ell_1 s_2 \dot{q}_2 \\ 0 & \ell_1 c_2 \dot{q}_2 \end{bmatrix} B(q)\dot{q} + J^{\mathsf{T}\,ad}(q)\tau + \ell_1 \ell_2 s_2 F_m \\ &\quad + K\left(J^{\mathsf{T}\,ad}(q) B(q)\dot{q} - \zeta\right) \\ r &= J^{\mathsf{T}\,ad}(q) B(q)\,\dot{q} - \zeta. \end{aligned}\right.$$

input torque

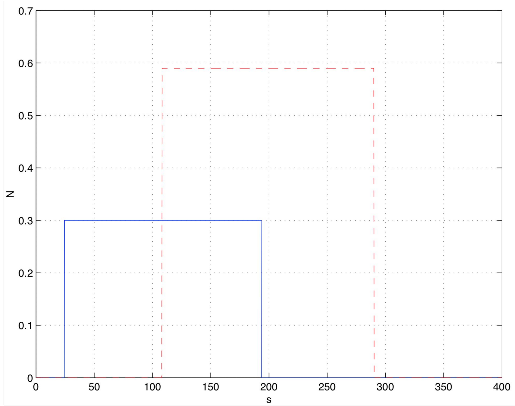
predicted FDI behavior in presence of force sensor faults f_F

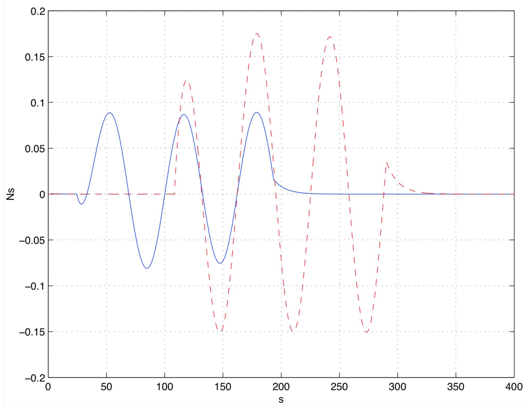
$$\boxed{\dot{r} = -K r + \ell_1 \ell_2 \sin q_2\, f_F}$$

Isolation of F/T sensor faults

- simulation on the 2R robot

bias faults on the two components of force sensor measurement

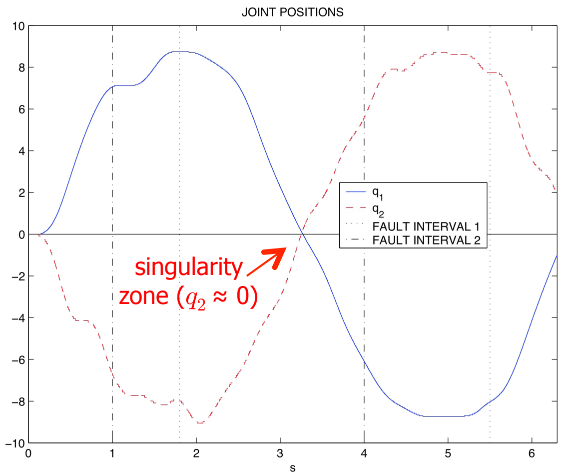


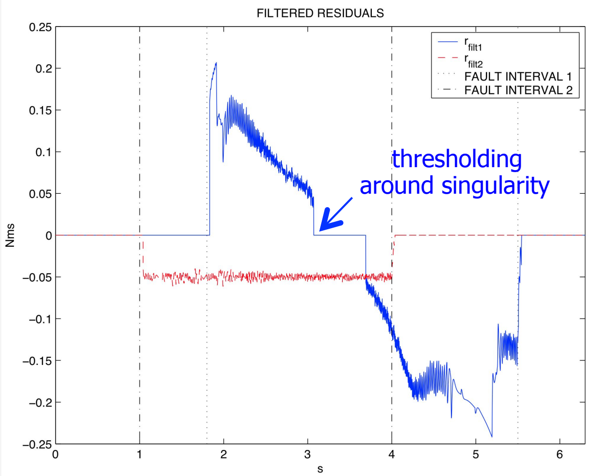


FDI residual components

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

evolution of joint variables





(filtered) residuals for bias (non-zero) measurement faults emulated on sensor:
-1N on F_x in [1.8,5.5]
0.05N on F_y in [1,4]

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 !
- assuming instead non-concurrency, e.g., of the 4 faults in the 2R robot

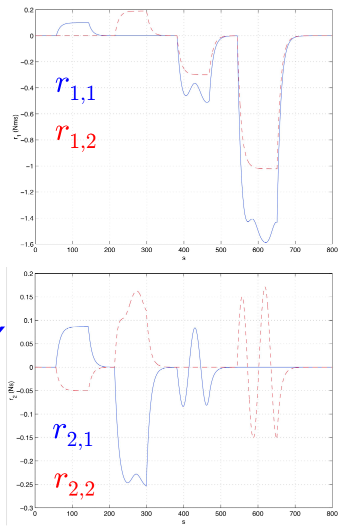
dependence of residuals on considered faults

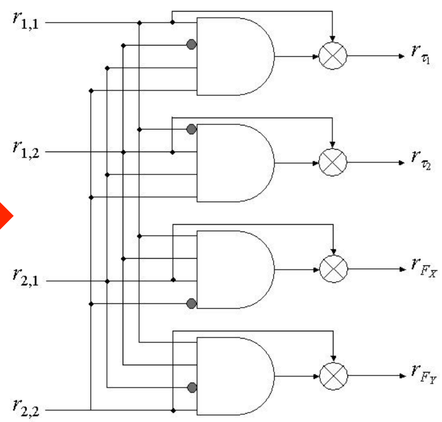
fault \ residual	$r_{1,1}$	$r_{1,2}$	$r_{2,1}$	$r_{2,2}$
f_{τ_1}	1	0	1	1
f_{τ_2}	0	1	1	1
f_{F_X}	1	1	1	0
f_{F_Y}	1	1	0	1

isolation matrix

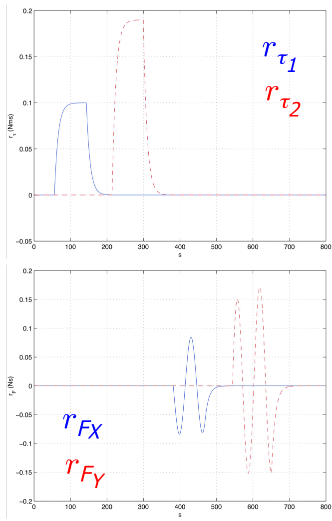
$r_{1,1}\, r_{1,2}$ \ $r_{2,1}\, r_{2,2}$	1 1	1 0	0 1	0 0
1 0	f_{τ_1}	NA	NA	NA
0 1	f_{τ_2}	NA	NA	NA
1 1	NC	f_{F_X}	f_{F_Y}	NA
0 0	NA	NA	NA	no fault

time sequence of non-concurrent faults: $f_{\tau_1} \to f_{\tau_2} \to f_{F_X} \to f_{F_Y}$





isolation logics



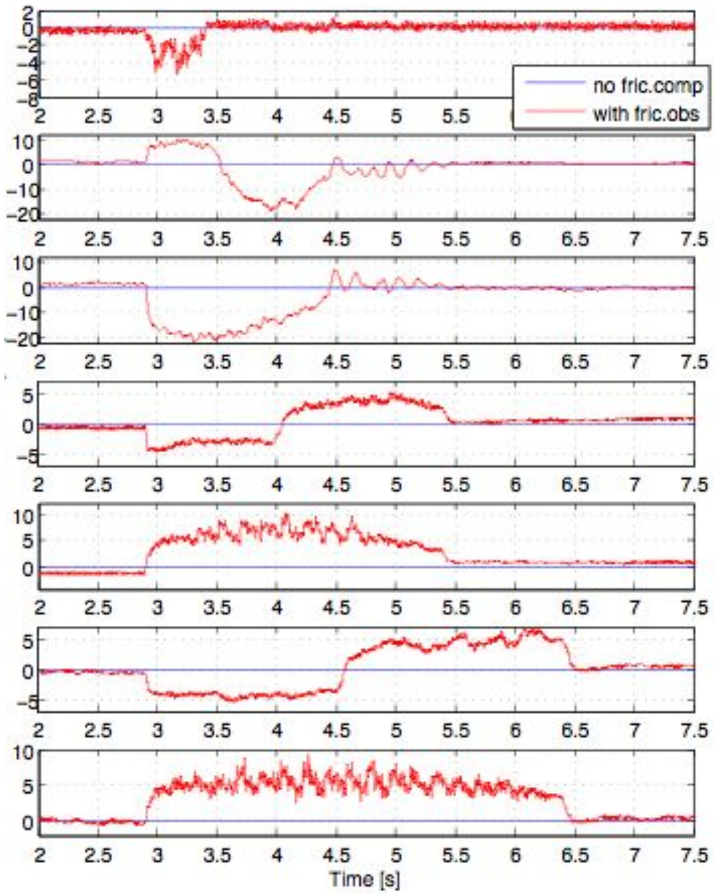
hybrid residuals allowing **isolation** of faults

Experiments on friction compensation

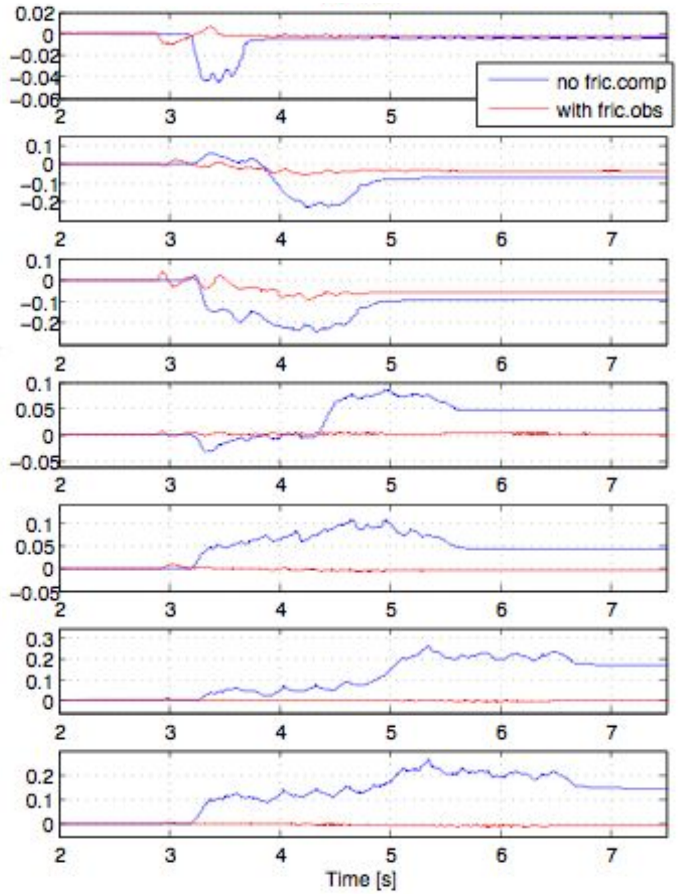
- results on the DLR 7R medical robot

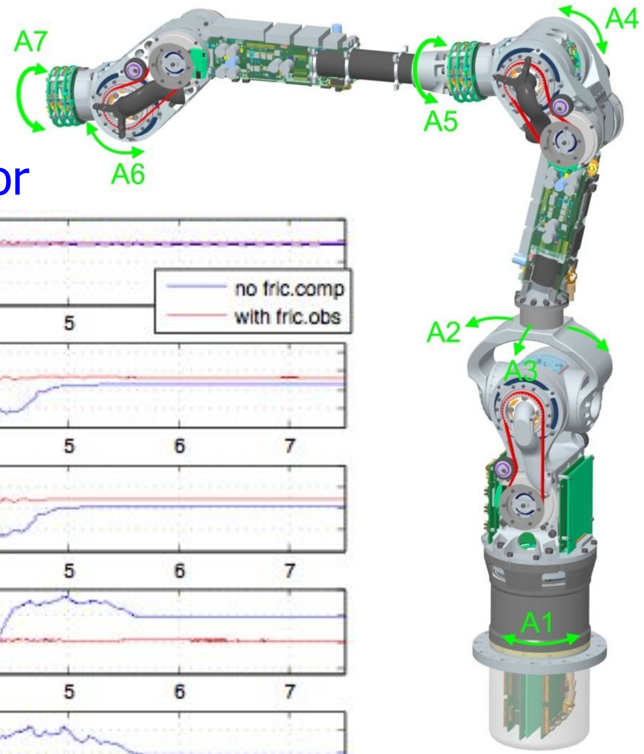
used in control law...

friction estimate via residuals



position error

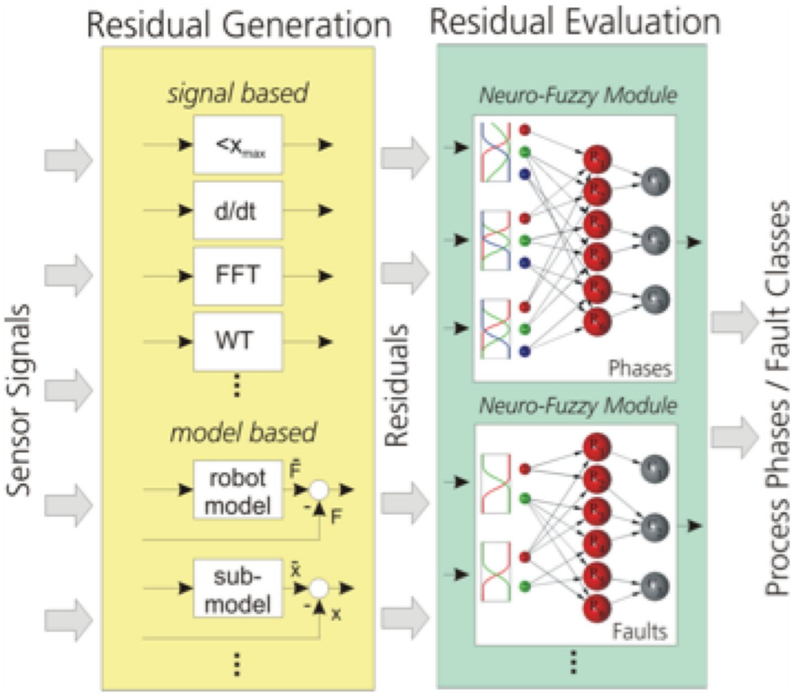


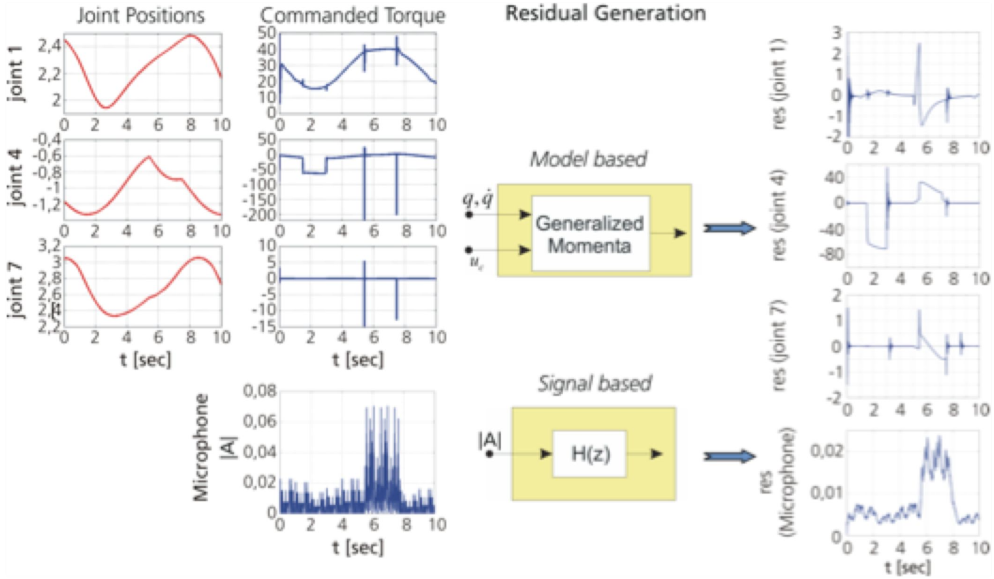


Model- and signal-based FDI

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

so as to obtain the “best of both worlds”





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