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Actuator Failure Detection and Isolation Using Generalized Momenta *

Alessandro De Luca   Raffaella Mattone

Dipartimento di Informatica e Sistemistica
Università degli Studi di Roma "La Sapienza"
Via Eudossiana 18, 00184 Roma, Italy
deluca@dis.uniroma1.it   mattone@labrob.ing.uniroma1.it

Abstract

We present a method based on the use of generalized momenta for detecting and isolating actuator faults in robot manipulators. The FDI scheme does not need acceleration estimates or simulation of the nominal robot dynamics and covers a general class of input faults. Numerical results for a $2R$ robot undergoing also concurrent actuator faults are reported. The method is extended to robots with joint elasticity and to the inclusion of actuator dynamics.

1 Introduction

For complex dynamic plants, the problems of fault detection and isolation (FDI) and of fault tolerant control (FTC) are of considerable interest. Detection consists in generating diagnostic signals (*residuals*) in correspondence to potential faults that may affect the system. Fault identification occurs when a residual allows discriminating a specific fault from other faults or disturbances. Once a FDI scheme is available, the control architecture and feedback laws can be reconfigured in order to obtain a reliable, fault tolerant performance. Lately, FDI techniques developed for linear systems [1] have been extended in several ways to systems with nonlinear dynamics [2, 3]. In most approaches, residuals are generated by comparing the output of a dynamic observer with the measured system output.

In particular, FDI schemes have been proposed for robot manipulators, a class of nonlinear systems with a well-defined analytical model. The faults of interest are in this case the failure of joint position or velocity sensors and that of joint force/torque actuators [4], the latter having received much more attention in the literature. In [5], a nonlinear observer is built for the robot system state while actuator fault isolation is achieved by weighting the residual vector with the inertia matrix. In [6], a discrete-time observer is designed for both sensor and actuator fault detection. These approaches require the inversion of the inertia matrix, since they include the on-line simulation of the robot dynamics. A different class of FDI schemes is based on dynamic parameter estimation. In [7], failure is detected by comparing the current parameter estimates with their nominal values, while in [8] an adaptive scheme is used to identify a constant degradation of the commanded actuator torque. These approaches were shown to be effective only for specific types of fault. Note also that actuator FDI for robot manipulators would be trivial if joint acceleration measures were available. An approach that avoids the estimation of joint acceleration as well as the inversion of the inertia matrix, while covering a general class of actuator faults, has been recently proposed in [9]. It is based on the comparison of the nominal input torque and of the full nonlinear dynamic robot model, both passed through a stable linear first-order filter.

In this paper, we present an actuator FDI method for robot manipulators having the same nice properties of [9], but explicitly based on the use of the robot *generalized momenta*. This allows several interesting outcomes: *i)* the actual computations involved in the actuator FDI scheme can be reduced; *ii)* the same FDI concept can be extended in a straightforward way also to other classes of electro-mechanical robotic systems; *iii)* the equivalent structure of nonlinear observer is easily recovered for the proposed FDI scheme. In addition, no assumption is made on the availability of a reference robot motion and on the presence of a stabilizing feedback controller.

The paper is organized as follows. Modeling of robot dynamics with actuation faults and a classification of typical faults are described in Sect. 2. The basic FDI scheme is presented in Sect. 3. Simulation results are reported in Sect. 4 for a $2R$ planar robot under gravity. Further extensions are given in Sect. 5

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and a discussion, including issues on an adaptive version of FDI schemes, concludes the paper.

2 Modeling

We consider rigid robot manipulators having n joints (with associated generalized coordinates q) that may undergo input faults. Using a Lagrangian approach, the standard robot dynamic model is

$$M(q)\ddot{q}+c(q,\dot{q})+g(q)+F_v\dot{q}+F_s\text{sign}(\dot{q}) = u-u_f, \quad (1)$$

where $M(q) > 0$ is the (symmetric) inertia matrix, $c(q, \dot{q})$ is the Coriolis and centrifugal vector, $g(q)$ is the gravity vector, $F_v \geq 0$ and $F_s \geq 0$ are, respectively, the viscous and static friction (diagonal) matrices, u are the commanded (nominal) torques, and u_f are the (unknown) fault torques.

Each component of vector $c(q, \dot{q})$ is quadratic in the velocities $\dot{q}$

$$c_i(q,\dot{q}) = \frac{1}{2}\dot{q}^T C_i(q)\dot{q}, \qquad i=1,\ldots,n, \qquad (2)$$

where the (symmetric) matrices $C_i(q)$ are computed through the Christoffel symbols as

$$C_i(q) = \left[\frac{\partial m_i(q)}{\partial q}\right] + \left[\frac{\partial m_i(q)}{\partial q}\right]^T - \left[\frac{\partial M(q)}{\partial q_i}\right], \quad (3)$$

being $m_i(q)$ the i-th column of the inertia matrix $M(q)$.

By eq. (1), we capture any type of actuator fault and in particular all the following potential faults on the generic i-th input channel:

- *total actuator fault*: $u_{f,i} = u_i$, i.e., there is no more actuation at the joint i which becomes free swinging;
- *partial actuator fault*: $u_{f,i} = \varepsilon u_i$, with $\varepsilon \in (0,1)$, representing a 'weakening' of the actuator torque capability;
- *locked actuator fault*: $u_{f,i} = u_i - \tau_i$, where τ equals the left-hand side of eq. (1) (see also [9]);
- *actuator bias*: $u_{f,i} = b_i$, with constant polarization b_i;
- *actuator saturation*: $u_{f,i} = u_i - \text{sign}(u_i)\, u_{i,\max}$, where $u_{i,\max} > 0$ is the maximum absolute torque allowed (symmetric w.r.t. the origin);
- *collision fault*: $u_{f,i} = j_i^T(q)F$, where F is the force/torque due to collision with the environment at a generic location along the robot and $j_i(q)$ is the i-th column of the associated Jacobian $J(q)$.

3 Failure detection and isolation

In the following, we shall make some standing assumptions for our FDI design.

1. Only the (nominal) input torque u is available to the FDI scheme (obviously, not u_f).
2. No specific input $u(t)$ is considered, i.e., it may be generated as a pure *feedforward command* or as a (stabilizing) *feedback control* law.
3. No specified motion $q_d(t)$ is prescribed; in particular, $q(t)$ may also grow unbounded over time.
4. Input faults may be *permanent* ($(u_{f,i}(t) \neq 0$ for $t \geq T)$ or *intermittent* ($u_{f,i}(t) \neq 0$ for $t \in [T_i, T_e]$); also, *concurrent* faults ($u_{f,i}(t) \cdot u_{f,j}(t) \neq 0$, $i \neq j$, for some t) are included.
5. Measurement of the full state $(q, \dot{q})$ is available; indeed, velocity $\dot{q}$ may be estimated by numerical differentiation of q, as measured by high-resolution encoders.
6. A correctly identified robot dynamic model is available (see, however, Sect. 6 for a discussion on an adaptive version of the FDI scheme).
7. No other disturbance is present.

These assumptions deserve some comments. Assumptions 2 and 3 are very convenient because they separate the behavior and performance of the FDI system from the specific required task and the used stabilizing controller. Assumption 4, which reflects the most general situation, requires the FDI system to generate an asymptotically stable residual vector signal, in order to determine that fault recover is occurring, and that each scalar residual associated to an input channel is decoupled from the others. As for the strength of assumption 7, it is possible to show that, for mechanicla systems modeled by eq. (**1**), a general necessary condition for being able to achieve FDI on an input channel [3] is always violated in the presence of unstructured disturbances acting on the same channel. However, the proposed FDI scheme for input channel i will also work in the presence of disturbances on different channels $j \neq i$.

The FDI design is based on the simple but powerful idea of *generalized momenta* $p = M(q)\dot{q}$. In fact, one can write the following first-order dynamic equation

$$\dot{p} = u - u_f - \alpha(q,\dot{q}), \qquad (4)$$

where, using eqs. (1–3), the components of $\alpha(q, \dot{q})$ are given, for $i = 1, \ldots, n$, by

$$\alpha_i = -\frac{1}{2}\dot{q}^T \frac{\partial M(q)}{\partial q_i}\dot{q} + g_i(q) + F_{v,i}\dot{q}_i + F_{s,i}\text{sign}(\dot{q}_i). \quad (5)$$

Note that in α only part of the Coriolis and centrifugal terms c are present. It is also evident from eq. (4) that each fault (and nominal input torque) affects one and only one component of p. In particular, this decoupling allows identifying separately concurent actuator faults.

Let the *residual vector* r be defined by

$$r = K\left[\int (u - \alpha - r)dt - p\right], \quad (6)$$

with (diagonal) $K > 0$. In order to be implemented, eq. (6) requires $(q, \dot{q})$ and the nominal input u but no acceleration $\ddot{q}$ nor inversion of the inertia matrix $M(q)$. The residual dynamics satisfies

$$\dot{r} = -Kr + Ku_f, \quad (7)$$

namely that of a *linear exponentially stable* system driven by the fault u_f. Actually, for every component of the residual dynamics we can write a transfer function

$$\frac{r_i(s)}{u_{f,i}(s)} = \frac{K_i}{s + K_i}, \quad i = 1, \ldots, n$$

having unitary gain. In principle, for very large values of K_i the evolution of $r_i(t)$ reproduces accurately the evolution of the fault $u_{f,i}(t)$.

For the sake of analysis, the structure of a nonlinear dynamic observer (with linear error dynamics) [3] can be easily recognized by formally rewriting a copy of eq. (4), with state $\hat{p}$, driven by the state error $p - \hat{p}$ in place of u_f, and having r as output, i.e.,

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

Note that this is a standard observer for a class of nonlinear systems, where nonlinear terms are functions of measurable outputs only [10, p. 203].

It should be noted that the obtained result is similar to the FDI proposed in [9], but requires less computations (the integral of α instead of the filtering of the whole left-hand side of eq. (1)). In addition, the idea of using generalized momenta for designing an input FDI scheme is rather general and can be extended to other mechanical and electro-mechanical robotic systems as well (see Sect. 5).

4 Simulation results

For testing the proposed actuator FDI scheme, we have considered a $2R$ planar robot moving in the vertical plane (under gravity) and neglecting joint friction. The dynamic model (1) takes the form

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

where $(q_1, q_2) = 0$ is the horizontal straight configuration, the expression of the dynamic coefficients a_i can be found, e.g., in [11, pp. 152], and we have used a shorthand notation for sine/cosine. The robot links are assumed to be uniform rods of length 0.5 m and masses 20 and 10 kg, respectively.

In this case, the evaluation of α from eqs. (5) yields

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

being $M(q)$ independent of q_1 (cyclic coordinate).

We assume that the robot starts at rest in the downward equilibrium configuration and is subject for 25 s to sinusoidal (joint 1) and square wave (joint 2) nominal open-loop torque inputs, as shown in Fig. 1. The two actuators undergo an intermittent total failure during the time intervals

$$[T_{i,1}, T_{f,1}] = [15, 20], \quad [T_{i,2}, T_{f,2}] = [12, 18],$$

so that there are concurrent faults for $t \in [15, 18]$ s. The actual (unknown) torques driving the mechanical structure are shown in Fig. 2. The (faulted) evolutions of the joints in Fig. 3 provide no evidence neither of the faults occurrence nor of their localization and recover. On the other hand, the residual evolutions in Fig. 4 (obtained with $K = \text{diag}\{50, 50\}$) shows the practical recostruction of the faults, which equal the 'missing' nominal torques, and a totally decoupled behavior.

A second set of simulations refer to the addition of a (bandwidth-limited) white noise disturbance torque on the first input channel. Two situations are considered: non-colocated fault of the second actuator (Figs. 5–6) and colocated fault of the first actuator (Figs. 7–8). In the first case, the second residual is unaffected by the non-colocated disturbance while the first residual returns a filtered version of the disturbance. A similar behavior is obtained in the colocated case. Since it is theoretically not possible to decouple an unstructured disturbance from a fault when they act on the

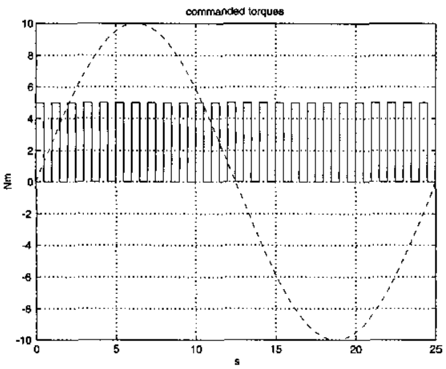

Figure 1: Nominal applied torques (without fault): joint 1 (red/- -), joint 2 (blue/—)

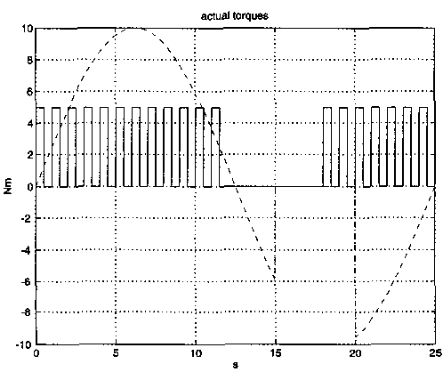

Figure 2: Intermittent total fault of both actuators: actual torque 1 (red/- -) and torque 2 (blue/—)

same input channel, fault detection relies in this case on the relative amplitudes of the disturbance and of the actuator fault. In general, a priori information on the potential faults and on the nature of unmodeled disturbances can be used to set constant or adaptive thresholds for fault detection (see, e.g., [9]). For simulation results with other types of fault, see [12].

5 Some extensions

We present here the extension of our FDI design to two other model classes of robot manipulators, one in the presence of transmission elasticity concentrated at the joints, the other including the dynamics of DC electrical motors. For ease of illustration, we neglect the presence of friction and other dissipative effects.

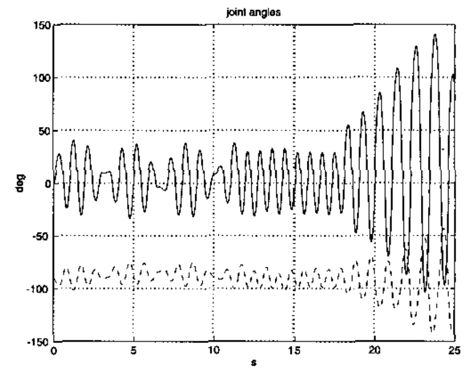

Figure 3: Joint evolution in the presence of actuator fault: joint 1 (red/- -), joint 2 (blue/—)

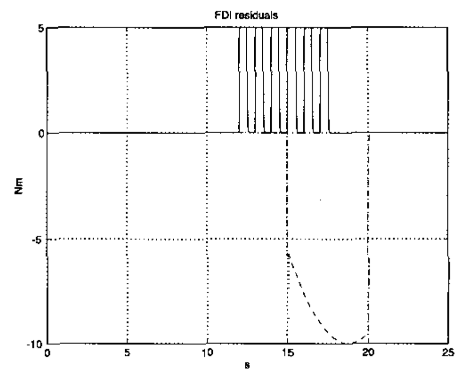

Figure 4: Residuals: joint 1 (red/- -), joint 2 (blue/—)

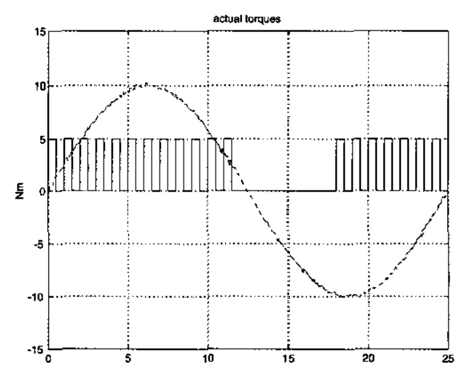

Figure 5: Fault at second joint and disturbance at first joint (non-collocated case): actual torque 1 (red/- -) and torque 2 (blue/—)

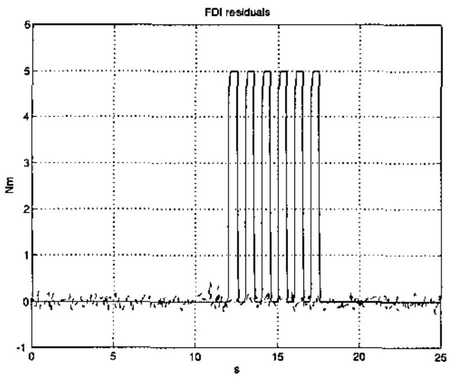

Figure 6: Residuals for fault at second joint and disturbance at first joint (non-collocated case): joint 1 (red/- -), joint 2 (blue/–)

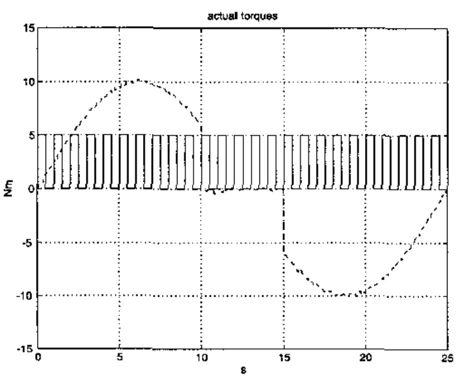

Figure 7: Fault and disturbance collocated at first joint: actual torque 1 (red/- -) and torque 2 (blue/–)

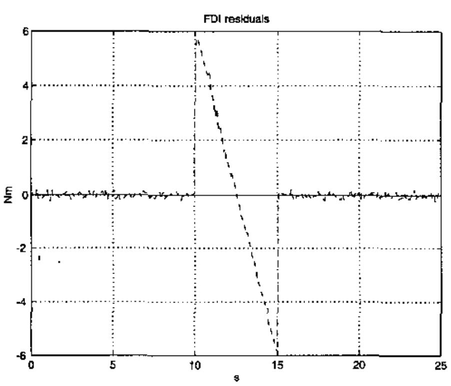

Figure 8: Residuals for fault and disturbance collocated at first joint: joint 1 (red/- -), joint 2 (blue/–)

5.1 Robots with elastic joints

The dynamic model of robots with joint elasticity is given in terms of link coordinates q and motor coordinates θ and consists of the $2n$ second-order differential equations [13] (including the actuator fault torque u_f)

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) + K_e(q-\theta) = 0 \qquad (8)$$

$$J\ddot{\theta} + K_e(\theta - q) = u - u_f. \qquad (9)$$

Equation (8) refers to the dynamics of the links and contains the same terms defined in eq. (1), plus the elastic torque transmitted through the joints with (diagonal) stiffness matrix $K_e > 0$. Equation (9) expresses the motor dynamics, with the effective actuator inertia (diagonal) matrix $J > 0$.

The generalized momenta p and vector α are partitioned as

$$p = \begin{bmatrix} p_q \\ p_\theta \end{bmatrix} = \begin{bmatrix} M(q)\dot{q} \\ J\dot{\theta} \end{bmatrix},$$

and

$$\alpha = \begin{bmatrix} \alpha_q \\ \alpha_\theta \end{bmatrix} = \begin{bmatrix} -\frac{1}{2}\mathrm{col}\left\{\dot{q}^T \frac{\partial M}{\partial q_i}\dot{q}\right\} + g(q) + K_e(q-\theta) \\ K_e(\theta - q) \end{bmatrix}.$$

Since faults occurr on the motor dynamics, we are interested only in the behavior of p_θ, namely

$$\dot{p}_\theta = u - u_f - \alpha_\theta$$

The residual r_θ is defined as (with diagonal $K > 0$)

$$r_\theta = K\left[\int [u - K_e(\theta - q) - r_\theta]dt - J\dot{\theta}\right], \qquad (10)$$

and satisfies the same linear equation (7). Interestingly enough, the FDI implementation requires in this case knowledge of the partial state $(\theta, \dot{\theta}, q)$ (not of the link velocity $\dot{q}$) and only of the matrices J and K_e (but not of the full link dynamics!). In addition, due to the diagonality of the matrices involved in eq. (10), a fully decentralized FDI scheme is obtained.

5.2 Including actuator dynamics

Consider again the robot dynamic model (1) and include the presence of DC electrical motors driven by the input voltage v on the armature. The overall dynamic equations (including input voltage faults $v_{f,j}$) are

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) = K_T i \qquad (11)$$

$$L_j \frac{di_j}{dt} + R_j i_j + K_{B,j}\dot{q}_j = v_j - v_{f,j}, \;\; j = 1,\ldots,n, \qquad (12)$$

where the scalar eqs. (12) refer to the armature equivalent electrical motor loops (with inductances $L_j > 0$, resistances $R_j > 0$, and back emf constants $K_{B,j} > 0$), i is the vector of armature currents, and $K_T > 0$ is the current-to-torque (diagonal) matrix.

Following our approach (and notation of Sect. 3), we generate the following set of decoupled residuals

$$r_j^{[v_j]} = K_j^{[v_j]} \left[\int (v_j - R_j i_j - r_j^{[v_j]}) dt - L_j i_j - K_{B,j} q_j \right],$$

with $K_j^{[v_j]} > 0$, for $j = 1, \ldots, n$. The residuals satisfy linear dynamic equations of the form

$$\dot{r}_j^{[v_j]} = -K_j^{[v_j]} r_j^{[v_j]} + K_j^{[v_j]} v_{f,j}, \qquad j = 1, \ldots, n.$$

Note that the FDI of v_f is decentralized since it needs only the values of the electrical parameters local to the faulted actuator and the local measures of i_j and q_j.

6 Discussion

The use of generalized momenta provides a natural and efficient method for detecting and isolating actuator faults in robot manipulators, without the need of inverting the robot inertia matrix. This method is general enough to handle also the inclusion of joint elasticity or of motor dynamics in the robot plant model. In these cases, the method allows to exploit the intuitive fact that generalized momenta are 'closer' to the input fault locations, leading to intrisically decentralized FDI schemes.

Once a total actuator fault has been detected, a FTC strategy should reconfigure the controller to one designed for the resulting underactuated mechanical system (see, e.g., [14] for the case of a planar $2R$ robot without actuation at the second joint).

In order to remove the assumption on the availability of an accurate dynamic model, an adaptive version of the proposed FDI scheme can be developed, following similar guidelines as in [9]. Adaptation modifies the dynamic parameters in eq. (6) (or in eq. (1)) until the residual vanishes for a given motion task.

We should note, however, that such adaptive FDI schemes require that parameter adaptation preceeds the occurrence of faults; moreover, in the absence of convergence of dynamic parameter estimates to their true values, there is no guarantee that the residual remains zero at the beginning of a new motion task, even in the absence of faults. We are currently working in order to overcome these two limitations.

Finally, we have performed a preliminary experimental validation of our approach on the Quanser Pendubot and have extended it to the sensor FDI problem, in particular for failures of a force/torque sensor [12].

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