FAULT DETECTION OF THE ACTUATOR BLOCKING
Experimental Results in Robot Control Structures

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Abstract: In this paper is presented an algorithm, which allows for a certain robotic structure, under the terms of an actuator blocking occurrence during the operation, either a correct positioning (if it is possible) or a positioning in an acceptable proximity of the desired coordinates by minimising an optimal criteria (through the adequate commands to the functional elements). The paper is proposing the synthesis of the commands for a poly-articulated robotic arm (3 segments). First, a workspace analysis is made, then is presented the algorithm for the actuators, first in the terms of a normal operation (finding the optimal motions) and second in the terms of the blocking of some robotic segments.

1 INTRODUCTION

The correct positioning of the robot control arm is critical to the efficient operation in the applications of poly-articulated robot arms. One of most important problem in robot control is the detection and isolation of faults occurring in the actuators. In this case it is necessary to develop a control algorithm for certain robotic structure, under the terms of actuator blocking occurring during the operation. This algorithm must provide a correct positioning of the gripper or a positioning in an acceptable proximity of the desired coordinates using an optimal criterion. The fault detection and isolation (FDI) problem is an inherently complex one. Good diagnostic performances without installing supplementary equipment, force the diagnostic tools developers to use techniques available to process all information that is "hidden" in the technological process. Numerous approaches have been developed to address the problem of FDI in dynamically systems, including the fault trees and parity space techniques (Viswanadham, 1987, 1988), Kalman filters (Meril, 1984), and detection filters (Iserman, 1997), etc.

This paper describes the application of a fault detection and isolation method based on linear or nonlinear parameter model of the robot arm. A new closed loop control method achieves the actuator's fault isolation and control in fault conditions.

2 FAULT DIAGNOSIS

A fault causes degradation in system behaviour but does not necessarily cause complete failure of plant operation. The system may continue functioning to a lesser degree, though failure may occur if a fault is not detected in time. The tasks of a fault detection system are (Vinatoru, 1997), (Ivanescu , 2000):

- *Fault detection* - a binary indication if the fault is present or the system is fault-free.
- *Fault isolation* - that means the knowledge of which sensor or actuators have failed.
- *Synthesis of commands* in fault conditions which must assure the viability of the system (possibly in a slightly degraded manner).

In figure 1 is presented a generalised structure of the model based on fault detection and isolation.

In the design of automatic control systems, a great emphasis is put on the structures capable to detect and isolate fault conditions. The new solutions can be classified in two different categories:

a) Fault detection and identification using dedicated observers, detection and identification algorithms;
b) Fault management using FDIM architecture and simulation results.

For the later category, in figure 2 we present a structure for fault detection and isolation that assures fast detection of a fault described thru a parameter in the mathematical model.

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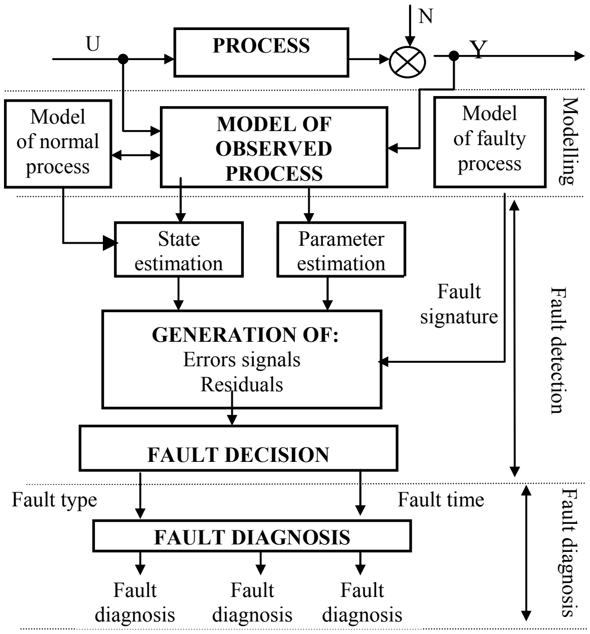

Figure 1: Generalised structure of model based fault detection and isolation methods.

Let consider the plant described by the system:

$$\bar{x} = f(\bar{x}, \bar{x}_c, \alpha)\,; \quad y = C^T.\bar{x} \tag{1}$$

where $\bar{x}$ is the state vector, y the measurable output, α is a fault parameter and x_c is the control command. The real controller (PI type to ensure the steady state errors equal with zero), is described by:

$$\dot{x}_c = K_R(\dot{v} - \dot{y}) + K_I(v - y) \tag{2}$$

where *v* is the set point of the control system.

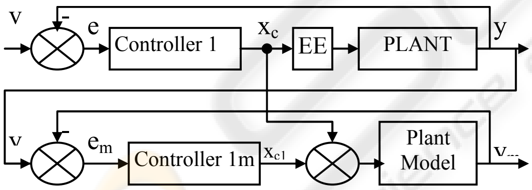

Figure 2: FDI Structure.

The control structure for fault detection (fig. 2) includes a plant model described by:

$$\dot{\bar{x}}_m = f(\bar{x}_m, \bar{x}_c + \bar{x}_{c1}, \alpha_m)\,; Y_m = C^T \cdot x_m \tag{3}$$

and the control signal:

$$\dot{x}_{c1} = K_R(\dot{y} - \dot{y}_m) + K_I(y - y_m) \tag{4}$$

Replacing variables $\dot{y}$ *and* $\dot{y}_m$ in (6) we get:

$$\dot{x}_{c1} = K_R C^T f(\bar{x}, \bar{x}_c, \alpha) - K_R C^T f(\bar{x}_m, x_{c1}, \alpha_m) + K_I C^T(\bar{x} - \bar{x}_m) \tag{5}$$

The FDI control structure, if designed properly, will modify the control signal x_{c1} to obtain $e_{ms} = \lim_{t\to\infty} e_m(t) = 0$. Therefore,

$$Y_s = Y_{ms} \Rightarrow Y - Y_m = C^T(\bar{x} - \bar{x}_m) \to 0 \tag{6}$$

In this case, considering the steady state regime we get:

$$\lim_{t\to 0}\left[f(\bar{x}, \bar{x}_c, \alpha) - f(\bar{x}_m, \bar{x}_{c1}, \alpha_m)\right] = 0 \tag{7}$$

Using the linear model system (8) of the equations (1) and (3):

$$\begin{aligned} \dot{\bar{x}} &= A\cdot\bar{x} + b\cdot x_c + d\cdot\alpha \\ \dot{\bar{x}}_m &= A\cdot\bar{x}_m + b\cdot x_c + b\cdot x_{ci} + d\cdot\alpha_m \end{aligned} \tag{8}$$

after a few simple transformation in equations (7) and (8) we get the diference between faulty components real α and modelled α_m:

$$\alpha - \alpha_m = \frac{b}{d}\cdot x_{cs} \tag{9}$$

From the precedent analysis it results:
- the plant model shall reproduce the real plant ;
- the FDI control structure shall be asymptotically stable, using the plant model controller;
- the response time of the FDI structure shall be smaller than the response time of the real plant;
- the perturbations that appear in the real process shall be included, as much as possible, in the model structure.

3 SYSTEM ANALYSIS WITH FAULT ACTUATORS

For analysis of the behaviour of the robot arm, when one or many joints are blocked, we consider the configuration presented in fig. 3. From this figure, for the command θ_{ir} we can write the relations (10):

$$\theta_{ir} = (1 - k_i)\theta_i + k_i\theta_{i0}\,, \ i = 1,2,3 \tag{10}$$

in which: $k_i = 0$, for fault free actuator; $k_i = 1$, in fault conditions and the actuator blocked in θ_{i0} position.

In figure 3, θ_{ir} has the significance of the real command for the joint i. For the case when $k_i = 1$, we can simulate one actuator that don't work and remain in blocked position θ_{i0}. In conclusion, the occurance of one fault is equivalent with a jump modification of the state equation structure for the actuators.

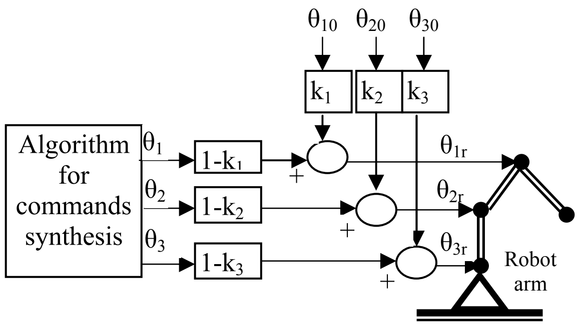

Figure 3: Synthesis of failed actuators.

The vector of commands has the expression:

$$\Theta_r = \begin{bmatrix} \theta_{1r} \\ \theta_{2r} \\ \theta_{3r} \end{bmatrix} = (I - K_D) \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} + K_D \begin{bmatrix} \theta_{10} \\ \theta_{20} \\ \theta_{30} \end{bmatrix} \qquad (11)$$

in which: K_D=diag $[k_1\ k_2\ k_3]$ is called the fault matrix. If $K_D \equiv 0$ the system has no fault.

The vector: $[\Theta_0]^T = [\theta_{10}\ \theta_{20}\ \theta_{30}]$ (12)

represent the blocking position of the actuators.

Therefore, we can study the behaviour in fault conditions, using a fixed fault matrix.

4 STRATEGY OF CONTROL IN FAULT CONDITIONS

Using the equations of robotic arm joints and the arm tip (Ivanescu 2000), we define the following fault situations and the domains of the fault free joints.

Zone I – first joint blocked (J_1):

$$\theta_1 - blocked,\ \theta_2 \in (0, \frac{\pi}{2}),\ \theta_3 \in (0, \frac{\pi}{2}) \qquad (13)$$

Zone II – second joint blocked (J_2):

$$\theta_1 \in (0, \frac{\pi}{2}), \theta_2 - blocked, \theta_3 \in (0, \frac{\pi}{2}) \qquad (14)$$

Zone III – third joint blocked (T):

$$\theta_1 \in (0, \frac{\pi}{2}),\ \theta_2 \in (0, \frac{\pi}{2}),\ \theta_3 - blocked \qquad (15)$$

The equation of arm tip (T) defines the limits of the work areas of the arm tip. For the case when $\theta_i = 0^0$ (suppose that i joints are blocked in this positions, i=1, 2, 3), these areas are presented in figure 4. There is a part of the fault free space of arm tip (zone 0) that cannot be covered. In figure 4 it is presented the movement of the zone I as function of the θ_1 parameter modifications. In the figure 5 it is presented the work area for the joint 3 (J_3) and the arm tip (T) for the situation when θ_3 is blocked at 90^0. The border of each zone is a reunion of quarter circle arcs with well known centre and radius. In this case the strategy of control presented by the same authors in (Ivanescu 2000) can be simplified. The proposed algorithm is presented in following steps:

Step 1. Setting up a database in the memory of the robot control computer with the border of the robot fault zones, and the rotation centres.

Step 2. Setup the control structure presented in fig.3 of paper (Ivanescu, 2000).

Step 3. The residual vector $r(t)$ created by "Fault detection and isolation block" offers the number $k \in (1,2,3)$ of blocked joint.

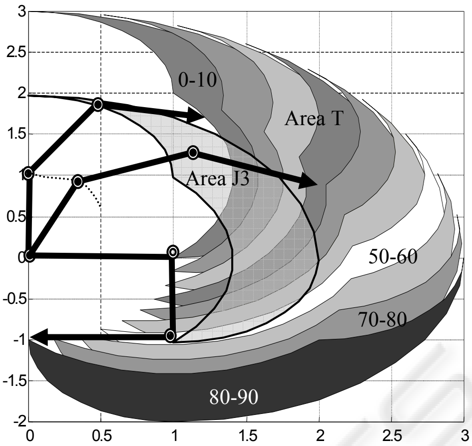

Figure 4: The movement of Zone I for $\theta_1 \in (0\text{-}90)$.

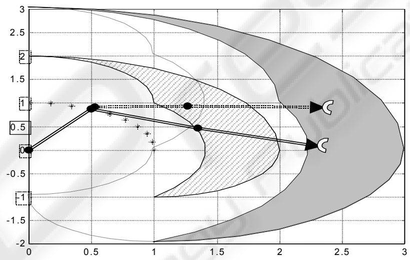

Figure 5: The robot control in fault condition (θ_3=0).

Step 4. Checking if the final position (x_k^3, y_k^3) of the robot arm tip is inside of the border of the zone k.

If the result is "*NOT*" the computer generate an alarm signal "*Can't touched the final position*". If the result is "YES" the computer executes the control algorithm, (Ivanescu, 2000), but only the step for fault free joints. In figure 5 is presented the movement of the robot arm tip for initial conditions I to position 1 by θ_1 and θ_2 control (θ_3 is blocked at 0^0) and the next step is the movement of the arm tip from 1 to 2 only with control $\Delta\theta_2$ because the points 1 and 2 are situated in the intersection of zone III for $\theta_3 = 0$ and zone I for θ_1 =fixed in the position of last command for point 1.

5 APPLICATION OF ROBOT MODELS

Our goal is to detect the faults by measuring the accessible process variables in real time. For the given process, these variables are the actuator's positions θ_{1r}, θ_{2r}, θ_{3r} and the griper position X_g (figure 3). There is a strong interdependence between these variables and the possible defects occouring in

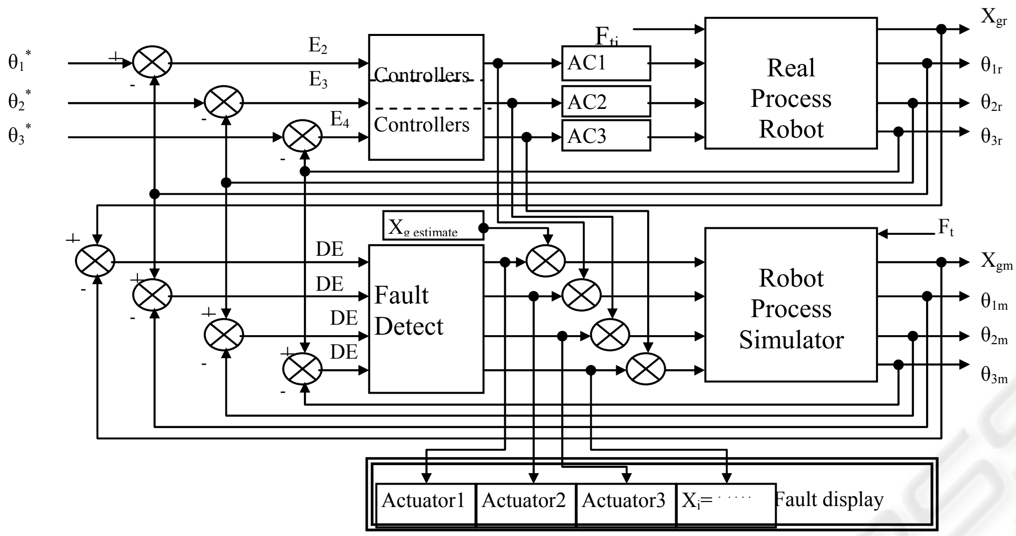

Figure 6: Fault detection block diagram.

the control equipment, and this impose an adequate method to choose the fault measurable outputs pairs.

In order to chose the corect perturbation-output pairs, we use the sensitivity matrix method. For experimental studies we implemented the fault detection structure presented in figure 6, as extension of the elements presented in the first part of the paper (figure 2).

The structure can be easily implemented in the robot supervising computers that collect information about the robot arm. This structure does not require supplimentary equipment, and it can be implemented for the existing monitoring digital control system of the robot.

6 CONCLUSIONS

In this paper it is presented an extension of the algorithm developed in authors' paper (Ivanescu, 2000). The results of this algorithm are:

- The resolute decision in fault conditions to continue or not the movement of robot arms
- The diminution of the control times
- The diminution of memory space allocated for database.
- The use of a simple algorithm for control implemented on a small controller.

In the future it is possible to develop some control algorithms in fault free conditions using the fault zone definitions. As a result of this analyse it is possible to develop the control of the robot arm only with one or two joint command.

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