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Fault tolerant control with respect to actuator failures Application to steam generator process

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Abstract

This paper deals with the analysis of nonlinear reachability and fault tolerant properties of multiactuator nonlinear systems. In this case, the process is a steam generator process containing a set of actuators. After occurrence of one or several actuator faults detected and isolated by Fault Detection and Isolation (FDI) approaches, a quantitative analysis of the faulty system properties helps us to determine whether the faulty system can go on operating or not. Nonlinear reachability analysis that has been presented in this paper allows us to determine the minimal number of actuators that are necessary to keep the system under control.

Keywords: Fault Detection and Isolation, Fault Tolerant Control, nonlinear reachability, actuator failures, steam generator process.

1. Introduction

Fault tolerance is highly required for modern complex control systems. Sensors, actuators or process failures may drastically change the system behavior, ranging from performance degradation to instability. Fault tolerant control systems are needed in order to preserve the ability of the system to achieve the objectives that has been assigned, or if this turns to be impossible, to assign new objectives so as to avoid catastrophic behaviors. Fault tolerant control implements the solution of control problem in which the system objectives can be achieved in spite of faults. The design of fault tolerant controllers needs the system to remain controllable in the presence of failures. Controllability or reachability (the ability of a state or a functional of a state to be controlled or reached by the inputs) is a property which characterizes the system and its actuators.

In this paper, we intend to characterize the nonlinear reachability of a system under actuator failures, and to identify those subsets of actuators whose failure keeps that system property unchanged, thus providing the control engineer with fault reconfiguration possibilities. Before studying fault tolerant properties based on the analysis of nonlinear reachability, we suppose that the faulty actuators are detected and isolated by an FDI algorithm such as structural analysis, based on the elimination of the

unmeasured variables of the system and only the healthy actuators are used to reconfigure the control law.
Generation of residuals could be based on the technique of structural analysis (Blanke et al., 2003). This approach consists in finding analytical redundancy relations which contain only known variables. Those relations are satisfied if the residuals are null during the normal system functioning and non-null when the system fails. The bipartite graph is built representing the process model. This graph is constituted by a set of nodes related each over by a set of arcs. Each node represents a variable of the system or a function related those variables. From this bipartite graph the incidence matrix and then the residuals are obtained. The set of residuals generates a binary sequence where “0” represents a null residual and “1” a non-null residual. Those binary sequences are called signatures. By comparing those signatures with theoretical, known signatures representing the faults , faulty actuators can be deduced.
Fault tolerance of sensor (namely fault tolerance estimation) systems has recently been studied in nonlinear systems based on the use of observability indices (Lienhardt *et al*, 2004). Because of the non duality between observability and controllability of nonlinear systems, the results can not be extended to fault tolerance analysis of actuator systems. Then, the definition of non linear reachability in terms of the Lie algebra (Isidori, 1997) has been used.
The proposed analysis rests on the definition of minimal and redundant actuator sets using the individual nonlinear generic reachability indices. Some properties of redundancy and minimality are introduced with reference to the system reachability. Minimal redundancy means that the loss of any actuator causes the system to be uncontrollable and redundancy means that the loss of subset of actuators remains the system to be unreachable (the functional of state is based on the healthy actuators).
The properties of the minimal and redundant sets are analyzed and used in order to build an algorithm which uses redundancy degrees for actuator losses. For some given degree (or/and reliability) the reachability property in the case of actuator failures could be guaranteed. Fault tolerance control strategy in the case of actuator faults can be represented by figure 1.

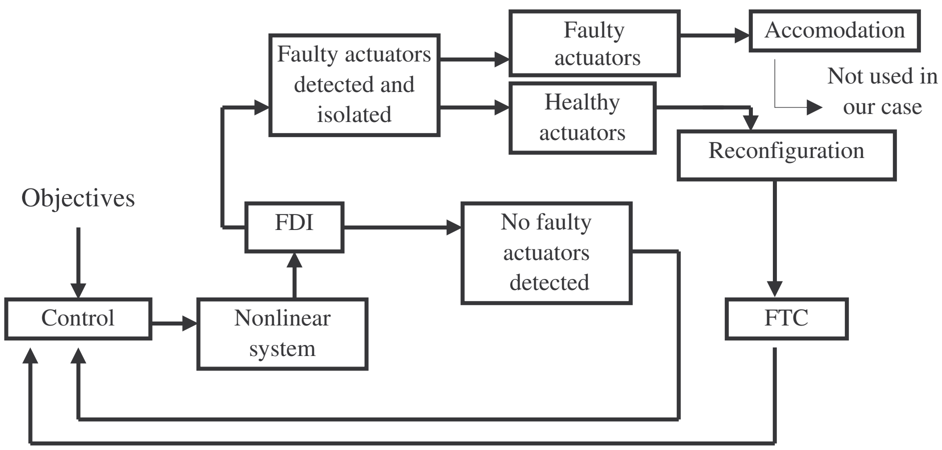

Figure 1. Fault tolerance control strategy

Our paper is organized as follow: description of the steam generator process, reachability analysis, redundancy and minimality and application to the steam generator process.

2. Process description

Let us consider the pilot process whose global view is shown on figure 2. The test plant designed to be a scale-model of part of a nuclear plant is a complex nonlinear system. This installation is mainly constituted of four subsystems: a receiver with the feed water supply system, a boiler heated by a 60kW resistor (steam generator), a steam flow system, and a complex condenser coupled with a heat exchanger.
In the present paper is considered only a part of the pilot process composed of the steam generator and the steam flow system as shown on Figure 2. The dynamic global model can be consulted in (Thoma and Ould Bouamama, 2000). The feed water flow, taken from the receiver tank, is pressurised via the feed pump which is controlled by a relay to maintain a constant water level inside the steam generator. The heat power is determined based on the available accumulator pressure. When the accumulator pressure drops below a minimum pressure, the heat resistance delivers maximum power; on the contrary, when the accumulator reaches a maximum pressure, the electrical feed of the heat resistance is cut off. As state variables used: the internal steam generator temperature T_{GV}, the total mass stored by the boiler M_{GV}, the mean temperature of the body of the boiler T_{MG} and the displacements of the control valves Z_{V1} and Z_{V2}. As inputs used: the inlet feedwater flow Q_{AL}, the heating power P_{TH}, the pressure imposed by the external system (condenser) P_{EC} and the control signals O_{VC} and O_{VT} acting respectively to the valves V_{M1} (automatically controlled valve) and V_{M2} (manually controlled valve)

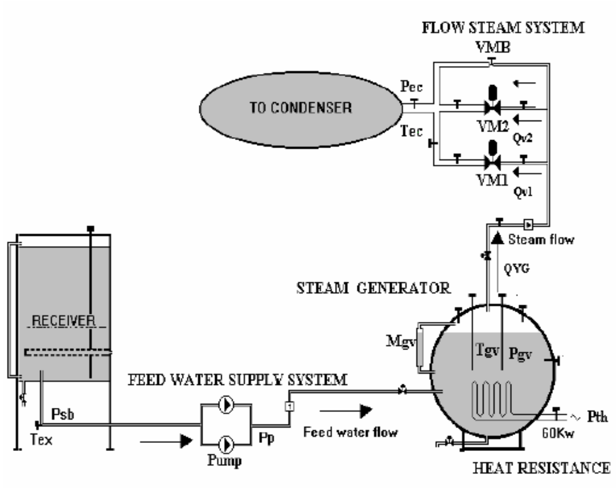

Figure 2. Technological schematic of the model

According to some modelling hypothesis, the simplified nonlinear state space model of the steam generator process is given by:

$$\begin{cases} \dot{T}_{GV}=\lambda_1\frac{Q_{AL}}{M_{GV}}+\lambda_2\frac{(T_{GV}-T_{MG})}{M_{GV}}+\lambda_3\frac{P_{TH}}{M_{GV}}-\frac{Q_{AL}T_{GV}}{M_{GV}} \\ \dot{T}_{MG}=\lambda_4(T_{GV}-T_{MG}) \\ \dot{Z}_{V1}=\lambda_5 Z_{V1}+O_{VC} \\ \dot{Z}_{V2}=\lambda_5 Z_{V2}+O_{VT} \\ \dot{M}_{GV}=\lambda_6(K_{V1}-K_{V2})T_{GV}^4+(K_{V1}-K_{V2})P_{EC}+Q_{AL} \end{cases} \quad (1)$$

where the state vector is: $x(t)=\left(T_{GV}\ T_{MG}\ Z_{V1}\ Z_{V2}\ M_{GV}\right)^T$ and the input vector $u(t)=\left(P_{EC}\ P_{TH}\ Q_{AL}\ O_{VC}\ O_{VT}\right)^T$.

Parameters ($\lambda_1,\lambda_2,\lambda_3,\lambda_4$) depend on thermal capacity of the fluid and others coefficients. Parameters λ_5 and λ_6 have been identified (Thoma and Ould Bouamama, 2000).

Let's assume that the parameters λ_i (i=1,2,…,6) are constant. K_{v1} and K_{v2} respectively the position of valve V_{M1} and V_{M2} are given by the constructor.

3. Reachability analysis of the system

Definition (Isidori, 1997): a state $\bar{x}\neq 0$ is said to be reachable (from the origin) if, given $x(0)=0$, there exist a finite time interval $[0,T]$ and an input $\{u(t), t\in[0,T]\}$ such that $x(T)=\bar{x}$. If all states are reachable, the system is said to be completely reachable.

3.1 Reachability analysis of an affine nonlinear system

Given an affine nonlinear system:

$$\dot{x}=f(x)+\sum_{i=1}^{m} g_i(x)u_i \quad (2)$$

with m inputs $u_1,u_2,...,u_m$ where f and g_i are n dimensional vector functions.

Mathematically, the analysis of the generic reachability is generated in three steps:
The initial distribution is:

$$\Delta_0=span\{g_1,g_2,...,g_m\} \quad (3)$$

This is extended by Lie-brackets of f and g in the first step

$$\Delta_1=\Delta_0+[f,\Delta_0]=span\{g_1,...,g_m,[f,g_1],...,[f,g_m]\} \quad (4)$$

with $[f,g_i](x)=\frac{\partial g_i}{\partial x}f(x)-\frac{\partial f}{\partial x}g_i(x)$.

The second step then gives the following

$$\Delta_2=\Delta_1+[f,\Delta_1]+\sum_{i=1}^{m}[g_i,\Delta_1] \quad (5)$$

and recursively,

$$\Delta_{n+1}=\Delta_n+[f,\Delta_n]+\sum_{i=1}^{m}[g_i,\Delta_n] \quad (6)$$

The sequence terminates at k=k' if $\Delta_{k'+1}=\Delta_{k'}$ (at most, k'=n-1 where n is the dimension of the state). To conclude about the reachability, the last step consists of determining the dimension of $\Delta_{k'}$ which corresponds to the dimension of the reachable space. The system is generically reachable if and only if $\dim(\Delta_{k'}) = n$.

3.2 Individual generic reachability indices vector

The vector ν , defined such that $\nu = (\nu_1,...,\nu_m)$, $1 \le \nu_i \le n$, is the individual generic reachability indices vector, if $\nu_i \in \nu$ is the generic reachability rank of the system (1) :

ν_i is called the individual generic reachability indice of the input i.
In other words, the vector ν is the vector of individual generic reachability indices, if the integer ν_i is the dimension of the space generically reachable only by the actuator i.

3.3 Redundancy and minimum sets

Let's consider the following nonlinear system:

$$\dot{x} = f(x) + \sum_{j=1}^{m} g_j(x) v_j$$

Let I_c be a set of actuators, J be a subset of I_c and $I_c \setminus J$ its complementary in I_c.
Redundancy and minimality notion are introduced according to recovery possibilities of system instrumentation.

A set of actuators I_c is said minimal with respect to the state space if and only if :

$$\begin{cases} \Omega_{I_c} \subseteq \Omega \\ \forall J \subset I_c,\ \Omega_{I_c \setminus J} \not\subset \Omega \end{cases} \tag{7}$$

Where Ω_{I_c} and Ω are respectively the space recovered by the set I_c of actuators and by the state.
In other words, a set of actuators *Ic* is said minimal with respect to the state space if and only if the state space is generically reachable with *Ic* but generically unreachable with $Ic \setminus J,\ \forall (J \neq \varnothing) \subseteq I_c$
A set of actuators I_c is said redundant, if and only if :

$$\exists J \subseteq I_c \textit{ with } J \neq \{\varnothing\}, \text{ such that } \Omega_{I_c \setminus J} \subseteq \Omega \tag{8}$$

A loss of actuators in a minimal set makes the state space unreachable and a loss of actuators in a redundant set can lead either to another redundancy set either to a minimal set or to a set unable to keep the state space reachable.

4. Application to a steam generator process

The application is about a steam generator process in which:

$$f(x) = \begin{pmatrix} \lambda_2 \dfrac{(T_{GV} - T_{MG})}{M_{GV}} \\ \lambda_4 T_{GV} + \lambda_5 T_{MG} \\ \lambda_6 Z_{V1} \\ \lambda_6 Z_{V2} \\ \lambda_7 (K_{V1} - K_{V2}) T_{GV}^4 \end{pmatrix} \text{ and } g(x) = \begin{pmatrix} 0 & \dfrac{\lambda_3}{M_{GV}} \dfrac{\lambda_1}{M_{GV}} & -\dfrac{T_{GV}}{M_{GV}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ (K_{V1} - K_{V2}) & 0 & 1 & 0 & 0 \end{pmatrix}$$

The computation of the algorithm of section 3.1 leads to the results given in table 1:

Table 1. Reachability analysis of the steam generator process

State x_j \input u_i	u_1 P_{EC}	u_2 P_{TH}	u_3 Q_{AL}	u_4 O_{VC}	u_5 O_{VT}
x_1 (T_{GV})	1	1	1	1	0
x_2(T_{MG})	1	1	1	1	0
x_3(Z_{V1})	0	0	0	1	0
x_4 (Z_{V2})	0	0	0	0	1
x_5 (M_{GV})	1	1	1	1	0
ν_i	3	3	3	4	1

In table 1, x_j is generically reachable by the input u_i if and only if the cellular corresponding to the line of x_j and to the column of u_i is equal to 1.

Table 1 shows that state x_3 and x_4 are respectively generically reachable only by input u_4 and u_5. Also, u_4 can generically reach the state x_1, x_2,and x_5. So inputs u_4 and u_5 are necessary and sufficient to generically reach the state and therefore have to be detected and isolated without false alarms. So, the set of actuators $\{u_4, u_5\}$ is a minimal set of actuators. All sets of actuators which don't contain both actuators u_4 and u_5 are neither minimal or redundant. Finally, all sets of 3 actuators or more and containing actuators u_4 and u_5 are redundant. The choice of the set of actuators containing u_4 and u_5 depend on the desired weak redundancy degree (Lienhardt *et al*, 2004). For instance, if the desired weak redundancy degree is equal or up to 1, $\{u_1, u_2, u_4, u_5\}$,$\{u_1, u_3, u_4, u_5\}$,$\{u_2, u_3, u_4, u_5\}$,$\{u_1, u_4, u_5\}$,$\{u_2, u_4, u_5\}$,$\{u_3, u_4, u_5\}$ could be chosen. A reliability study could be computed in order to give the set of actuators having the best reliability.

5. Conclusion

Reachabilty studies in case of faulty actuators are used to determine minimal and redundant sets of actuators to keep the functional reachable and then to know the maximal number of actuators which can be lost while keeping the system reachable or controllable. Our approach depends on isolation of faulty actuators and only the best healthy actuators that satisfy the properties of fault tolerant control are used to reconfigure the system. Our work can be extended to the condenser model, which was previously used for Fault Detection and Isolation studies (Aitouche *et al*, 1999).

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