MULTIMODEL BASED FAULT TOLERANT CONTROL OF THE 3-TANK SYSTEM

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Abstract

The problem of fault-tolerant control of a 3-tank system benchmark process using multiple models and switching control is addressed in this paper. According to this approach, the possible modes of process operation, either due to changes in production regime and disturbances or to the occurrence of faults in sensors and/or actuators, are modelled by local linear predictive models. It is assumed that for each set of operating conditions there is a local controller which stabilizes it while embodying corresponding constraints. The fault-tolerant controller is made up by these local controllers, which commute among themselves according to the decision of a supervisor. The supervisor makes the decision by comparing the candidate local model behavior with the one of the plant and choosing the controller corresponding to the best fitted model. A minimum dwell-time for each controller is repected for stability reasons.

1 Introduction

Fault tolerant control arises as a natural answer to increasing demand for safety and reliability in complex systems. The aim of fault tolerant control is to ensure system operation at a minimum level in the presence of faults, gracefully degrading performance and minimizing damages. Two critical blocks of a fault tolerant control system are fault detection and diagnosis, and controller reconfiguration. Controller reconfiguration may imply a change in controller gains as well as different controller structures exploring redundant hardware (sensors, actuators or process parts) or even to radically change the mission.

In this paper the reconfigurability analysis is assumed to be done *a priori* using *e.g.* the methods in [6]. Thus, for each fault it is assumed that there are controller gains and/or structures fulfilling *a priori* defined operating requirements.

This paper addresses the problem of fault tolerant control of the 3-tank system benchmark process, using the multiple model controller switching approach.

The concept of multiple models and controller switching received attention in recent years where stability and robustness issues [1, 2, 3] have been studied. The basic idea is the following: either due to changes in operating regime or to the occurrence of faults, several types of process dynamic behavior may be yielded. Around each one, plant dynamics is described by a linear model, hereafter denominated "local model". For each local model, a local controller stabilizing it is designed. For ensuring stability, a minimum dwell time for each local controller is ensured. In this paper this strategy is applied to the 3-tank benchmark problem. Section 2 briefly decribes the 3-tank system, while section 3 presents the control algorithm. In section 4 simulation results are presented concerning this case study. Conclusions are addressed in section 5.

2 Description of 3-Tank System

The benchmark process [7] consists of 3 interconnected tanks, fig.1. Tank 3 is connected to tanks 1 and 2 through 2 pipes, one at the bottom of the tank and the other at half height. There are valves in each one of these pipes allowing either to simulate faults or to control the level of tank 3. There are also valves at the bottom of tanks 1 and 2 for simulating leaks and a valve on tank 2 which may control the output flow. The two pumps, P1 and P2, one at the inlet of tank 1, and the other at the inlet of tank 2, may be used to fill the tanks. The water level can be measured through 3 continuous water level meters, one at each tank. The structure of this process allows using tank 2 as redundant hardware (whenever necessary) if there is a leak on tank 1 or an obstruction between tanks 1 and 3. A full description of this process can be downloaded from *http://www.tu-harburg.de/rts* at the Hamburg University, from which this process is adapted.

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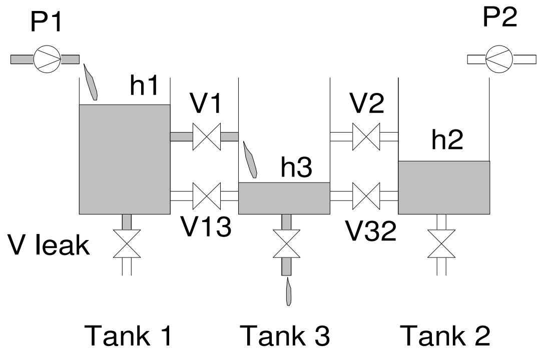

Figure 1: 3-tank system

3 Control Algorithm

Around each operating point defined by the occurrence of given faults and/or operating regime, the plant is assumed to be modeled by a discrete time linear time-invariant system: the aforementioned "local models". A linear local control is associated to each of the above local models.

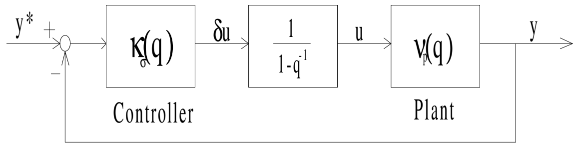

Figure 2: Feedback loop with the integrator, for constant plant and controller.

An integrator has been included in the loop in series with the controller in order to ensure zero steady-state error and smoth transition among controllers. Fig. 2 depicts the block diagram of the closed loop system for constant plant (index p) and constant controller (index σ). The following notation is used:

- y denotes the output (controlled) variable.
- u denotes the input (manipulated) variable.
- δu denotes the increments of u.
- y^* denotes the reference to be tracked by y.
- $k_\sigma(q)$ denotes the transfer function of the σ-th controller.
- $\nu_p(q)$ denotes the transfer function of the candidate p-th model.
- q denotes the forward shift operator.

When the plant operating condition, as defined by faults and/or operating regime, change, the index p of the candidate model $\nu_p(q)$ also changes. Thus, the controller should be provided with a mechanism for adjusting the index σ of the active controller transfer function, $k_\sigma(q)$, in order to match the operating conditions. Fig. 3 depicts a control system with such mechanism, hereafter refered as the *supervisor*.

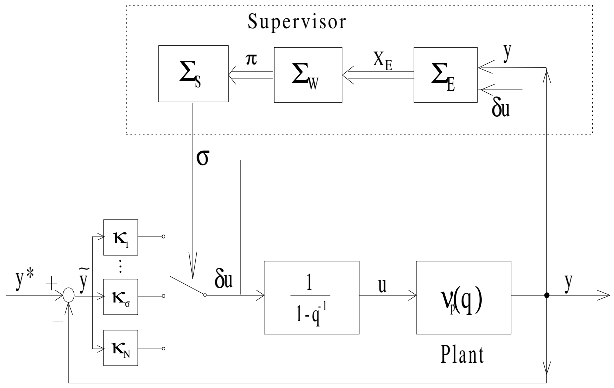

Figure 3: Feedback control loop and the supervisor.

3.1 The Supervisor

The supervisor used in this paper follows the structure proposed in [1, 4] and is detailed in fig. 4. It consists of three stages:

- A shared-state estimator, Σ_E.
- A performance weight generator, Σ_W.
- A switching logic scheme, Σ_S.

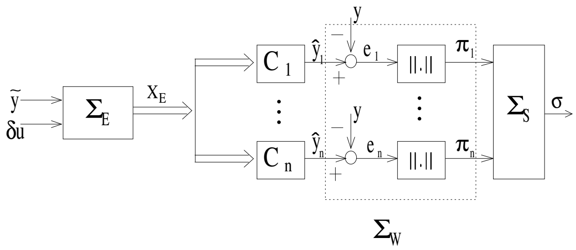

Figure 4: Shared-state estimator based supervisor.

The shared-state estimator Σ_E generates estimator plant outputs from a common state vector X_E, and a bank of predictive models. It is decribed by

$$X_E(t+1) = \begin{bmatrix} A_E & 0 \\ 0 & A_E \end{bmatrix} X_E(t) +$$

$$+ \begin{bmatrix} b_E \\ 0 \end{bmatrix} y(t) + \begin{bmatrix} 0 \\ b_E \end{bmatrix} \delta u(t) \tag{1}$$

$$\hat{y}_p = C_p X_E(t) \tag{2}$$

where (A_E, b_E) is a controllable pair. Thus, A_E and b_E are chosen as

$$A_E = \begin{bmatrix} 0 & 0 & 0 & 0 & \dots \\ 1 & 0 & 0 & 0 & \dots \\ 0 & 1 & 0 & 0 & \dots \\ 0 & 0 & 1 & 0 & \dots \\ \vdots & \vdots & & \ddots & \ddots \end{bmatrix} \quad b_E = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ \vdots \end{bmatrix} \tag{3}$$

and only C_p depends on the parameters of the $p-th$ plant model. The performance weight generator Σ_W computes a measure of the mismatch between the plant and each local model. One such measure is computed by a low pass filtering of the squared estimator errors.

$$\pi_i(t+1) = \pi_i(t)\lambda + (\hat{y}_i - y)^2 \tag{4}$$

where $\lambda < 1$ and π_i is the performance signal associated to the $i-th$ nominal process model. The lower π_i, the better the matching between the $i-th$ model and the operating conditions. If the change in the plant dynamics behavior is described by an hidden Markov model (HMM) a stochastic estimation method may be used as a measure of the matching between the candidate local model and the plant [8]. The aim of the switching logic scheme is to assure the stability of the overall system. If successive changes occur in the controller, there is a need for an hysteresis or a dwell time [1, 4] for guaranteeing stability. The switching logic scheme Σ_S used in this paper is defined in [4]. This algorithm switches among controllers, choosing the one with the best performance signal, and assuring a minimum period of time between each switch. This period of time is referred as *dwell time*.

3.2 Controller Design

For practical reasons the bank of local controllers is also implemented in a shared state form. The controller shared state is obtained by the following state equation.

$$X_C(t+1) = \begin{bmatrix} A_C & 0 \\ 0 & A_C \end{bmatrix} X_C(t) +$$

$$+ \begin{bmatrix} b_C \\ 0 \end{bmatrix} (y^*(t) - y(t)) + \begin{bmatrix} 0 \\ b_C \end{bmatrix} \delta u(t) \tag{5}$$

where (A_C, b_C) is a controllable pair. The increments of the control signal are given by

$$\delta u(t)_\sigma = f_\sigma X_C(t) + g_\sigma(y^*(t) - y(t)) \tag{6}$$

where f_σ and g_σ depends on the parameters of the σ-th local controller.

Several methods may be used to design the local controllers $k_\sigma(q)$. In this paper PID controllers were tuned for each of the candidate local models, $\nu_\sigma(q)$, corresponding to the different operating/faulty conditions.

The resulting controller gains define $k_p(q)$. The design of local control aims at minimizing the tracking error and the overshoot. It is however remarked that the different local controllers may embody different local objectives. For instance, small overshoot is crucial for avoiding spillover whenever there is a change in the operating condition driving one of the tank levels very close to the maximum. For a local controller designed for such situation, small overshoot is more important than minimizing tracking error. This will be illustrated below by an example.

4 Simulation results

Two situations are considered. In the first, fault accomodation requires only gain readjustment, while the second require the reconfiguration of the manipulated variable.

4.1 Parameter reconfiguration

Consider the plant described in fig. 1 where the manipulated variable is the velocity of pump P1 and the output variable is the level of tank 3. Two faults are considered:

- Fault 1: pipe from tank 1 to tank 3 partially obstructed (valve V1 blocked at 60 %)
- Fault 2: leak on tank 1

Thus, four operating conditions (OC) may be yielded.

- OC 1 - Normal
- OC 2 - V1 obstructed
- OC 3 - Leak on tank 1
- OC 4 - Both leak and obstruction

In this case the controller reconfiguration implies only parameter adjustment. The manipulated and controlled variables are the same in normal operation as under faulty situations. Thus, for each operating condition, a linear local model and a PID controller have been tuned and the gains recorded. This is summarized in tables 1 and 2.

Model no.	Valve V1	Vleak
1	100 %	0 %
2	60 %	0 %
3	100 %	100 %
4	60 %	100 %

Table 1: Operating conditions for the local models.

Control. no.	K	Ti	Td
1	1.0e-3	150 s	25 s
2	0.8e-3	250 s	40 s
3	0.8e-3	200 s	50 s
4	1.0e-3	250 s	60 s

Table 2: Parameters for the local PID controllers.

In these simulations the sampling time has been settled as $T_S = 20\,s$. For the filtering effect in the performance signal $\lambda = 0.5$ is used, and the dwell-time is choosen as $t_D = 3$ samples. A small dither noise (with power $\eta^2 =$ 0.25e-11) was added to the control signal.

The plant starts operating in normal mode (operating condition 1); operating condition 2 at $t = 1500$; operating condition 3 at $t = 3000$; and operating condition 4 at $t = 4500$. The reference (desired level in tank 3) is kept constant at 0.1 m.

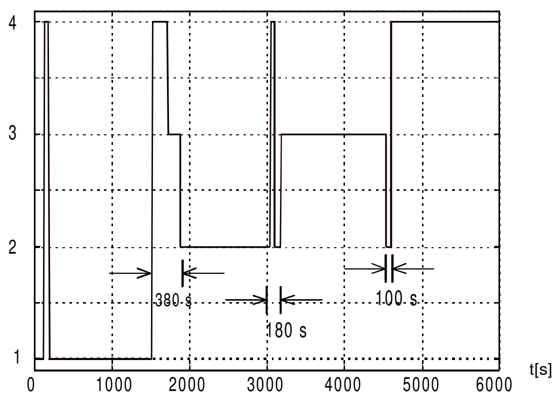

Figure 5: Supervisor output and delays between the switching of the plant and the correct decision of the supervisor.

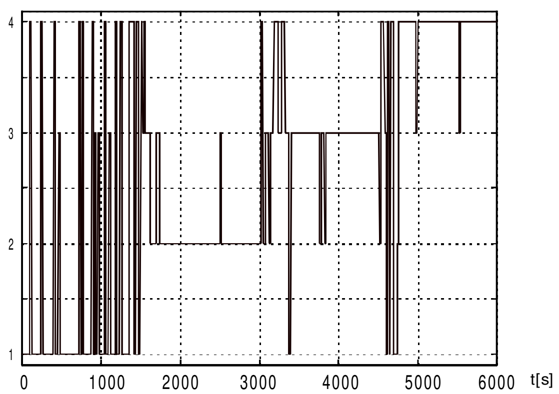

Figure 6: Supervisor output for $\lambda = 0$ (without filter in the performance weight generator).

Fig. 5 shows the evolution of the supervisor output. It is seen that the supervisor does not commute immediately to the correct model. The delay between the switch of the plant and the switch of the controller grows as λ goes to 1 (filter approaching an integrator).

However, it is not possible to reduce this delay by making λ close to zero. In fig. 6 the effect of $\lambda = 0.0$ is seen, the output of the supervisor becoming too unstable.

For $\lambda = 0.95$, fig. 7 shows the level of tank 3, with zero steady state error, and of tank 1, which does not overspill although the overshoot drives the level of tank 1 very close to the maximum.

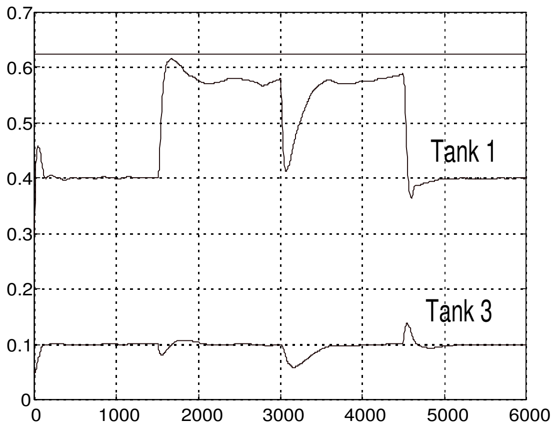

Figure 7: Water level on tank 1 and tank 3, with switching control.

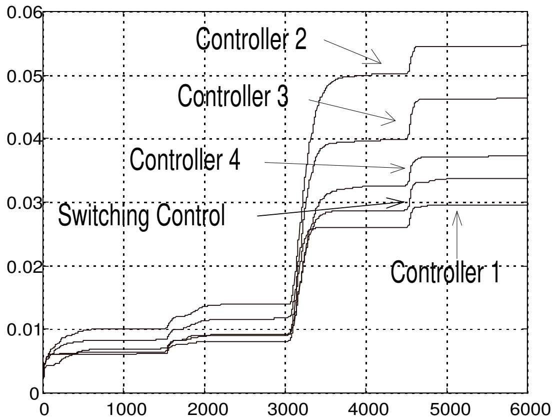

Figure 8: Quadratic error accumulated cost of switching control and PID controllers

Fig. 8 shows a comparison between the tracking performance of switching control and each one of the PID controllers, should it be used constantly. It can be seen that the minimum accumulated cost belongs to controller number 1, not to switching control. However, although controller no. 1 has a better tracking performance, it has a higher overshoot which causes a spillover in tank 1 around $t = 1500\ s$, as can be seen in fig. 9. This is no lucky incident, but corresponds to a change of control objective embedded in the design of the local controllers.

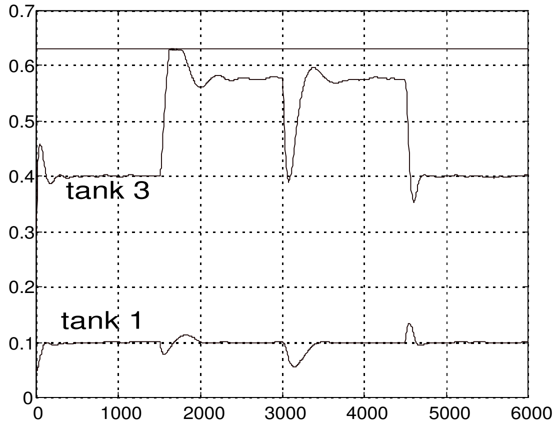

Figure 9: Water level on tank 1 and tank 3, with controller no. 1

4.2 Controller structure reconfiguration

Consider the benchmark process where now P1 controls the level h1 (PI controller), and the valve V1 controls the level h3 with an on-off controller. Three faults, which do not occur simultaneously, are considered:

- Fault 1: Valve V1 is closed and blocked
- Fault 2: Valve V1 is open and blocked
- Fault 3: Valve Vl is open (simulates a leak in tank 1)

In this case the reconfiguration task is to control the level h3 and minimize the loss of water in tank 1 (when considering fault 3). For this purpose, the control reconfiguration implies the use of the redundant hardware (tank 2), and the change of the manipulated variables. The effect of the faults (which occur at t=300 s) is seen in figures 10 to 12.

For each fault or operating condition a configuration has been *a priori* defined (table 3), as well as a linear model (eq. 7) of tank 1 to build the estimator.

$$h1(t+1) = C_1 h1(t) + C_2 P1(t) + C_3 V1(t) + C_4 \qquad (7)$$

Oper. cond.	Control loops	V1
Normal	V1→h3 and P1→h1	closed
Fault 1	V1 →h3 and P1→h1	manipul.
Fault 2	P1→h3	closed
Fault 3	P2→h3	closed

Table 3: Operating conditions and remedy actions.

The following simulations were performed with $T_s = 1s$ $\lambda = 0.93$ and for the PI controllers ($K_p = 0.001$, $Ti = 200s$). The simulations (figures 13 to 15) show the controlled system.

In these simulations only one fault occurs at a time. The supervisor decision is frozen after the fault detection, and the corresponding remedy action is applied.

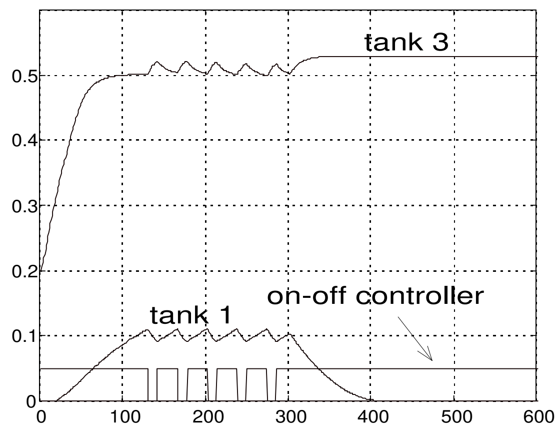

Figure 10: Fault 1 - Level on tank 1 and tank 3; Valve V1 controller.

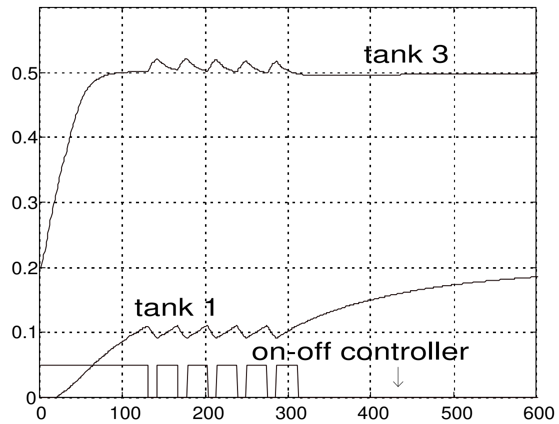

Figure 11: Fault 2 - Level on tank 1 and tank 3; Valve V1 controller.

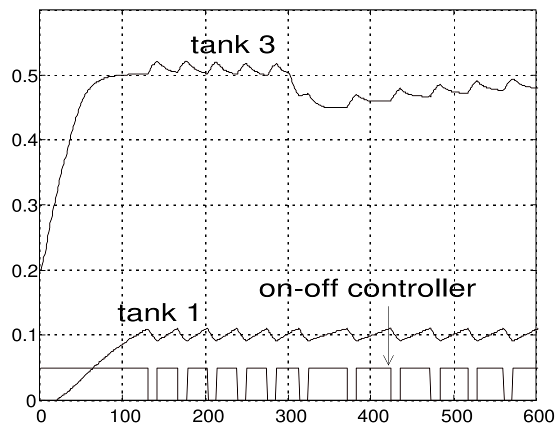

Figure 12: Fault 3 - Level on tank 1 and tank 3; Valve V1 controller.

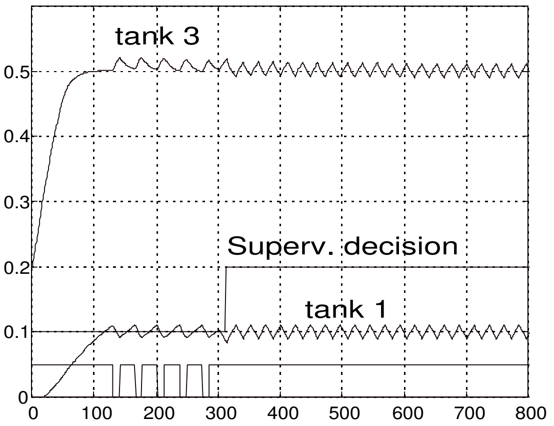

Figure 13: Fault 1 - Levels h1 and h3; Valve V1 controller; supervisor decision

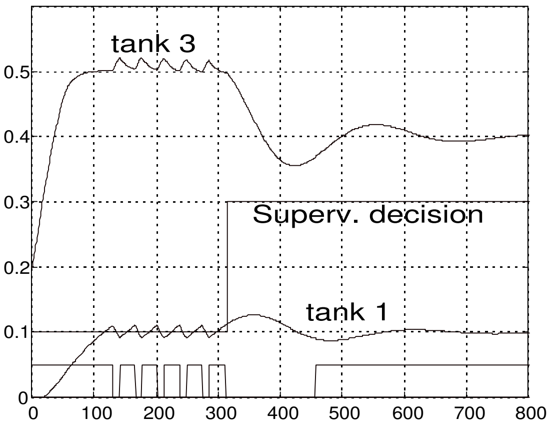

Figure 14: Fault 2 - Levels h1 and h3; Valve V1 controller; supervisor decision

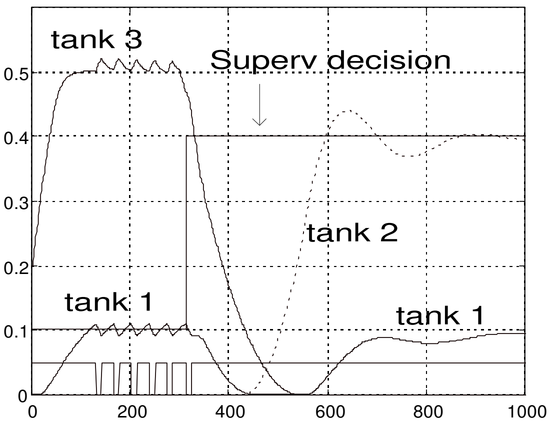

Figure 15: Fault 3 - Levels h1 and h3; Valve V1 controller; supervisor decision

In figure 15 the reconfiguration to cope with the leak in tank 1 implies the use of tank 2 as a buffer. In all simulations is observed that the multiple model based supervisor detects the correct fault after short time, while the controller acting accordingly.

5 Conclusions

This paper presents simulation results on the application of switching multiple model based fault tolerant control to a 3-tank system. The control structure used consists of a bank of candidate shared state controllers and a supervisor. Each of the candidate controllers is tuned in order to stabilize the plant in a region of the plant operating/faulty conditions. For that sake, PID controllers are tuned with each local model corresponding to plant operating conditions. The supervisor follows the structure proposed in [1, 4] consisting of a shared-state estimator, a performance weight generator and a dwell time switching logic scheme. The supervisor chooses the active controller corresponding to the predictive local model which best fits the plant data. Simulation results are presented showing the performance of this algorithm for fault detection and controller reconfiguration. The switching controller has been used to perform the parameter reconfiguration as well as controller structure reconfiguration.

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