Fault diagnosis for hybrid systems based on a bank of linear observers and a discrete automaton

Héla Gara¹ · Kamel Ben Saad¹

Received: 17 October 2019 / Accepted: 22 September 2020 / Published online: 9 October 2020
© Springer Nature Switzerland AG 2020

Abstract

This paper presents a fault diagnosis approach for a four-tank system considered as a hybrid dynamical system. The proposed diagnosis approach is based on a hybrid observer composed of a discrete automaton and a bank of linear observers. An automaton is used to improve the performance of the proposed method. For this study, we considered sensor, parametric and discrete faults. Simulation results showed the efficiency of the proposed diagnosis approach to detect and to localize the considered faults, despite the hybrid behaviors of the studied system.

Keywords Hybrid dynamical system · Four tank system · Fault diagnosis · Hybrid observer · Linear observers · Discrete automaton

1 Introduction

Nowadays, the modern production tools of some industrial systems are becoming more complex. So, the modeling of these systems has always been an issue. In fact, the system model is an abstraction of the real one. However, some complex systems combine continuous and discrete behaviors. These kinds of systems are called hybrid dynamical systems (HDS). HDS can be classified into several classes. Among them, we can cite switched linear systems, composed of a set of linear subsystems, called modes of functioning and controlled by a discrete events algorithm [1–4].

Reliability, availability, and safety have also become real issues for some industrial applications. Therefore, many fault diagnosis techniques have been proposed. They were used to detect and to localize the faults which can occur and generate damage in systems at any time. These techniques can be divided into two classes. The first one is based on mathematical models such as the parity space, observer and parametric estimation [5–7]. The second one

is based on artificial intelligence, artificial neural network or fuzzy logic and is called qualitative approaches [8].

Studying observability for the fault diagnosis of HDS has been the subject of several studies. The authors in [9] developed a diagnosis technique based on a bank of Luenberger observers ensuring the detection of sensor and parameter faults. In [10] a faults signature is generated by a switched robust observer to detect only single sensor fault. The convergence of the proposed observer by using the LMI conditions. Based on higher-order sliding mode observer, authors in [11] proposed an approach to detect the kind of faults that affect the continuous part of the switched linear systems. In [12], there are two designed observer methods for switched systems in the presence of sensor and actuator faults were proposed.

Indeed, a few works focused on the modeling of HDS for fault diagnosis that takes into account the interaction of the two parts: continuous and discrete. Authors in [13] presented a quantitative method based on the hybrid bond graph that describes the hybrid system behavior for the detection and the isolation of a single parametric

✉ Héla Gara, gara.hela2009@yahoo.fr; Kamel Ben Saad, Kamel.bensaad@enit.utm.tn | ¹LARA Laboratory, Université de Tunis El Manar, Ecole Nationale d'Ingenieurs de Tunis, le Belvédère, Bp 37, 1002 Tunis, Tunisia.

fault. A type of hybrid system modeling based on Petri nets coupling with fuzzy logics was proposed in [14] for fault diagnosis. In [15], hybrid systems with faults are modeled by using a formalism of the hybrid automaton. Hence, this method is doomed to detect and to distinguish faults.

Now and only now we proposed the design of a hybrid observer for fault diagnosis of a switched linear system. The hybrid observer is composed of two modules: a discrete automaton and a bank of linear observers. In fact, a discrete automaton is used to identify discrete events and therefore the mode of functioning. So, each observer is used to estimate the states of the identified mode of functioning. Indeed, by the estimation errors, named also residuals, a vector of residuals is generated. Contrary to [16], a stack of linear observers is required to diagnose faults which occur on the continuous part of the switched linear system. Here, the hybrid observer is designed to detect and to localize the continuous and the discrete faults. The proposed approach was applied on a four-tank system considered as a switched linear system and a particular class of HDS. Furthermore, this system is Multiple-Input-Multiple-Output (MIMO) nonlinear system characterized by some functioning modes corresponding to the states, on and off, of pumps and valves.

This paper is organized as follows. Section 2 presents four tanks system as an example of switched system. The proposed diagnosis approach is described in Sect. 3. The simulation results are given in Sect. 4. Finally, in Sect. 5 we will focus on the discussion.

2 Studied four tank system modeling

2.1 System description

The structure of the studied four-tank system is presented in Fig. 1. It is composed of two pumps, four interconnected tanks and a reservoir tank. The water is pumped up to the top two tanks, tank 1 and tank 3, through the two valves named v_1 and v_2 respectively. The cross-coupling between tank 1 and tank 3 is assumed by a valve named $v_3 \in \{0, 1\}$. The water level can be measured in the four tanks by four sensors.

This process can be modeled by the following equation composed of four nonlinear differential equations [17]:

Fig. 1 Structure of the studied four tank system

$$\begin{cases} \frac{dh_1(t)}{dt} = -\frac{s_1}{S_1} \sqrt{2gh_1(t)} + \frac{s_{13}v_3}{S_3} \sqrt{2g(h_1(t) - h_3(t))} \\ \quad + \eta u_1(t) \\ \frac{dh_2(t)}{dt} = \frac{s_1}{S_1} \sqrt{2gh_1(t)} - \frac{s_2}{S_2} \sqrt{2gh_2(t)} \\ \frac{dh_3(t)}{dt} = -\frac{s_3}{S_3} \sqrt{2gh_3(t)} + \frac{s_{13}v_3}{S_3} \sqrt{2g(h_1(t) - h_3(t))} \\ \quad + \eta u_2(t) \\ \frac{dh_4(t)}{dt} = \frac{s_3}{S_3} \sqrt{2gh_3(t)} - \frac{s_4}{S_4} \sqrt{2gh_4(t)} \end{cases} \quad (1)$$

where the following notations are used:

- S_i : cross section of tank number i ($i = 1 \dots 4$),
- s_i : cross section of outlet hole,
- s_{13} : outlet area between tank 1 and tank 3,
- h_i : water level for tank i ,
- g : gravitational constant,
- u_1 and u_2 : control signals,
- η : gain relating the control voltage with the water flow from the pump.

The model 1 can be linearized around an operating point. Thus, the linear state space representation of the studied system can be expressed as follows [18]:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \quad (2)$$

where

$$A = \begin{bmatrix} (-k_1 - k_{13}) & 0 & k_{13} & 0 \\ k_1 & -k_2 & 0 & 0 \\ k_{13} & 0 & (-k_3 - k_{13}) & 0 \\ 0 & 0 & k_3 & -k_4 \end{bmatrix}; \quad B = \begin{bmatrix} \eta & 0 \\ 0 & 0 \\ 0 & \eta \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

with : $k_1 = \frac{s_1 g}{s_1 \sqrt{2gh_{10}}}; k_2 = \frac{s_2 g}{s_2 \sqrt{2gh_{20}}}; k_3 = \frac{s_3 g}{s_3 \sqrt{2gh_{30}}};$
 $k_{13} = \frac{s_{13} g}{s_1 \sqrt{2g(h_{10} - h_{30})}}; k_4 = \frac{s_4 g}{s_4 \sqrt{2gh_{40}}}.$

We consider the state vector $x = [h_1 \ h_2 \ h_3 \ h_4]^T$, the input vector $u = [u_1 \ u_2]^T$ and the measured output vector $y = [h_1 \ h_2 \ h_3 \ h_4]^T$.

2.2 Switched linear system model

Generally, a switched linear system, composed of N linear subsystems, can be expressed by the following state space model [16]:

$$s_q \begin{cases} \dot{x}(t) = A_q x(t) + B_q u(t) \\ y(t) = C_q x(t) \end{cases} \quad q = 1 \dots N \quad (3)$$

where q is the index of the active mode at the instant, $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the input vector, and $y(t) \in \mathbb{R}^p$ is output vector.

The four-tank system is considered as a switched linear system because it contains both continuous and discrete elements. In fact, the appearance of discrete events implies changes in its continuous behavior. These changes are the results of the switching on and off of the two pumps and the valve v_3 . For this study, the valves v_1 and v_2 are open, and we suppose the knowledge of the active mode. Therefore, we can identify the three discrete events given in Table 1.

So, for the first mode of functioning ($q = 1$), the matrices of the state space representation are described as follows:

$$\begin{cases} A_1 = \begin{bmatrix} -k_1 & 0 & 0 & 0 \\ k_1 & -k_2 & 0 & 0 \\ 0 & 0 & -k_3 & 0 \\ 0 & 0 & k_3 & -k_4 \end{bmatrix} \\ B_1 = \begin{bmatrix} \eta & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}; \quad C_1 = C \end{cases} \quad (4)$$

For the second mode of functioning ($q = 2$), the matrices of the state space representation are described as follows:

$$\begin{cases} A_2 = \begin{bmatrix} -k_1 & 0 & 0 & 0 \\ k_1 & -k_2 & 0 & 0 \\ 0 & 0 & -k_3 & 0 \\ 0 & 0 & k_3 & -k_4 \end{bmatrix}; \\ B_2 = \begin{bmatrix} \eta & 0 \\ 0 & 0 \\ 0 & \eta \\ 0 & 0 \end{bmatrix}; \quad C_2 = C \end{cases} \quad (5)$$

For the third mode of functioning ($q = 3$), the matrices of the state space representation are described as follows:

$$\begin{cases} A_3 = \begin{bmatrix} -k_1 - k_{13} & 0 & k_{13} & 0 \\ k_1 & -k_2 & 0 & 0 \\ k_{13} & 0 & -k_3 - k_{13} & 0 \\ 0 & 0 & k_3 & -k_4 \end{bmatrix}; \\ B_3 = \begin{bmatrix} \eta & 0 \\ 0 & 0 \\ 0 & \eta \\ 0 & 0 \end{bmatrix}; \quad C_3 = C \end{cases} \quad (6)$$

3 Fault diagnosis based on hybrid observer

In this study, the proposed diagnosis approach is based on two modules. The first one is a discrete automaton which used to identify the current mode and to detect the discrete faults. The second one is a bank of linear observers used to generate residuals which are sensitive to a single sensor and parametric faults. Therefore, the designed hybrid observer-based fault diagnosis is proposed in Fig. 2 [19–21].

3.1 Residuals generation

In fact, the difference between the estimated outputs $\hat{y}_q(t)$, generated by the bank of observers, and the measured one $y_q(t)$, called the estimation errors, generates the residuals vectors noted $r_q(t)$.

Table 1 Discrete events for the three mode of functioning

Mode q	State of P_1	State of P_2	State of v_3	Time of mode q
1	On	Off	Off	[0 s, 600 s]
2	On	On	Off	[600 s, 1200 s]
3	On	On	On	[1200 s, 2000 s]

Fig. 2 Proposed diagnosis approach principle

Assuming all pairs (A_q, C_q) are observable, the Luenberger observer structure, for the switched linear system (3), is given as follows [9, 22]:

$$O_q \begin{cases} \dot{\hat{x}}(t) = A_q \hat{x}(t) + B_q u(t) + L_q (y_j(t) - \hat{y}_j(t)) \\ \hat{y}(t) = C_q \hat{x}(t) \\ r_q^j(t) = y_j(t) - \hat{y}_j(t) \end{cases} \quad q = 1 \dots N \quad (7)$$

where $\hat{x}(t) \in \mathbb{R}^n$ is the state estimation vector, $\hat{y}_j(t)$ means the j^{th} component of the estimated output vector, $r_q^j(t)$ is the j^{th} component of the residuals vector, L_q is the observer gain calculated for each active mode.

Therefore, the residuals vector is used as a fault indicator. Indeed, it is possible to detect any deviation of the nominal behavior of the system by comparing $r_q^j(t)$ with ε which has a value close to zero.

$$\begin{cases} r_q^j(t) \cong \varepsilon, & \text{no fault} \\ r_q^j(t) \neq \varepsilon, & \text{fault} \end{cases} \quad (8)$$

3.2 Discrete state automaton

The proposed discrete state automaton is a graphic description of a sequence of events changing the dynamical behavior of the HDS system [23].

A discrete state automaton is defined as 5-tuples $A = (Q, q_0, \Sigma, T, F)$ where:

- Q is a finite set of states,
- $q_0 \in Q$ is an initial start,

Table 2 Parameters of the studied four tank system

Parameters	Units	Values
$h_{10}; h_{20}; h_{30}; h_{40}$	m	$(q = 1) \rightarrow 0.31; 0.31; 0; 0$ $(q = 2) \rightarrow 0.31; 0.31; 0.13; 0.13$ $(q = 3) \rightarrow 0.21; 0.21; 0.20; 0.20$
$u_1; u_2$	V	4; 2.7
$S_1 = S_2 = S_3 = S_4$	m ²	0.01389
$s_1 = s_2 = s_3 = s_4 = s_{13}$	m ²	50.258×10^{-6}
η	m/sV	2.2×10^{-3}
g	m/s ²	9.81

- Σ is a finite set of input symbols called the alphabet,
- $T : Q \times \Sigma \rightarrow Q$ is a transition function,
- $F : F \subseteq Q$ is an acceptance state.

4 Simulation results

The proposed diagnosis approach, presented in the previous section, is applied to the studied four tank system characterized by the parameters given in Table 2.

For the studied system, three modes of functioning are defined as follows:

Mode 1 ($q = 1$):

$$\begin{cases} A_1 = \begin{bmatrix} -0.0146 & 0 & 0 & 0 \\ 0.0146 & -0.0146 & 0 & 0 \\ 0 & 0 & -0.0253 & 0 \\ 0 & 0 & 0.0253 & -0.0253 \end{bmatrix}; \\ B_1 = \begin{bmatrix} 0.0022 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}^T; \quad C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{cases} \quad (9)$$

Mode 2 ($q = 2$):

$$\begin{cases} A_2 = \begin{bmatrix} -0.0146 & 0 & 0 & 0 \\ 0.0146 & -0.0146 & 0 & 0 \\ 0 & 0 & -0.0253 & 0 \\ 0 & 0 & 0.0253 & -0.0253 \end{bmatrix}; \\ B_2 = \begin{bmatrix} 0.0022 & 0 & 0 & 0 \\ 0 & 0 & 0.0022 & 0 \end{bmatrix}^T; \quad C_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{cases} \quad (10)$$

Mode 3 ($q = 3$):

Fig. 3 Block diagram of the hybrid diagnosis approach principle

$$\left\{ \begin{array}{l} A_3 = \begin{bmatrix} -0.0976 & 0 & 0.0801 & 0 \\ 0.0175 & -0.0175 & 0 & 0 \\ 0.0801 & 0 & -0.0981 & 0 \\ 0 & 0 & 0.0179 & -0.0179 \end{bmatrix} \\ B_3 = \begin{bmatrix} 0.0022 & 0 & 0 & 0 \\ 0 & 0 & 0.0022 & 0 \end{bmatrix}^T \quad C_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{array} \right. \quad (11)$$

The gains of the matrices L_q are determined, by the pole placement method, in order to ensure the convergence and the stability of the Luenberger observers. Therefore, we choose the following matrices to ensure the asymptotic stability of the observers:

$$\left\{ \begin{array}{l} L_1 = \begin{bmatrix} 7.485 & 0 & 0 & 0 \\ 0.014 & 0.485 & 0 & 0 \\ 0 & 0 & 5.698 & 0 \\ 0 & 0 & 0.801 & 0.098 \end{bmatrix}; \\ L_2 = \begin{bmatrix} 7.485 & 0 & 0 & 0 \\ 0.014 & 0.485 & 0 & 0 \\ 0 & 0 & 6.477 & 0 \\ 0 & 0 & 0.022 & 0.877 \end{bmatrix}; \\ L_3 = \begin{bmatrix} 7.402 & 0 & 0.08 & 0 \\ 0.017 & 0.482 & 0 & 0 \\ 0.08 & 0 & 6.401 & 0 \\ 0 & 0 & 0.017 & 0.882 \end{bmatrix} \end{array} \right. \quad (12)$$

The block diagram of Fig. 3 shows the principle of hybrid observer-based fault diagnosis. The four-tank system can be affected by sensor faults and parametric faults.

Figures 4, 5 and 6 present the measured outputs of the studied system (h_1, h_2, h_3, h_4), the estimated outputs

Fig. 4 Measured outputs of the four tank system

Fig. 5 Estimated outputs of the four tank system

Fig. 6 Generated residuals by the hybrid observer

obtained from the proposed hybrid observer and the residuals $r_q^j(t)_{q \in \{1,2,3\}}$ respectively.

In our study, the objective of the system functioning is to maintain the water level in the four tanks for

Fig. 7 Discrete automaton

Fig. 8 The output of the discrete automaton

each mode on a well-defined level. The switching from one mode to another is governed by the water level $h_{i \in \{1,2,3,4\}}$.

Thus, the transitions condition depending on water level, which allow to follow of the normal mode succession are given as follows:

$$\begin{cases} T_1 : h_1 > 0 \text{ \& } h_2 > 0 \text{ \& } h_3 = 0 \text{ \& } h_4 = 0 \\ T_2 : h_1 \leq 30.14 \text{ \& } h_2 \leq 30.14 \text{ \& } h_3 > 0 \text{ \& } h_4 > 0 \\ T_3 : h_1 < 30.14 \text{ \& } h_2 < 30.14 \text{ \& } h_3 > 13.76 \text{ \& } h_4 > 13.76 \end{cases}$$

Figures 7 and 8 present the discrete automaton and the discrete evolution of the three modes of functioning for a normal operation respectively.

In fact, the discrete automaton is used in order to define each mode of functioning $q \in \{1, 2, 3\}$. So, by observing the corresponding change in the continuous dynamics, the transitions of the switched system can be detected.

Fig. 9 Residuals when the sensor fault occurs

Fig. 10 Estimated outputs when the sensor fault occurs

4.1 Sensor fault

For the case of a sensor fault affecting the tank 2 level sensor h_2 at the time $t = 1500$ s, the residuals and the estimated outputs are given by Figs. 9 and 10 respectively.

4.2 Parametric fault

In the case of a parametric fault, we consider a leak fault generate in the tank 2 at time $t = 1500$ s. This fault caused the reduction of the level h_2 . The differential equation of the tank level h_2 can be expressed as follows:

$$\frac{dh_2(t)}{dt} = \frac{s_1}{S_1} \sqrt{2g h_1(t)} - \underbrace{\left(\frac{s_2}{S_2} - \frac{s_f}{S_f} \right)}_{\text{Leak fault}} \sqrt{2g h_2(t)} \quad (13)$$

Fig. 11 Residuals when the parametric fault occurs

Fig. 13 The output of the discrete automaton

Fig. 12 Estimated outputs when the sensor fault occurs

Fig. 14 Estimated outputs when the discrete fault occurs

Figures 11 and 12, show the generated residuals and the measured outputs respectively, when the parametric fault occurs.

4.3 Discrete fault

The discrete automaton evolution may be affected by a discrete fault which is generated when the automaton stays in the current mode, whereas the transition condition of the next mode is normally getting over.

For this study, the discrete fault is generated when the state of one among the two pumps and the valve v_3 change during the time interval for each mode, contrary to the described scenario in Table 1. As an example, we supposed that a discrete fault occurs on account of the valve v_3 when its state stays off, at the time $t = 1200$ s. So, Figs. 13 and 14 present the evolution of the discrete automaton and the estimated outputs when the fault occurs.

5 Discussion

The fault diagnosis approach was evaluated in the four-tank system which is considered as a switched linear system. Indeed, the proposed approach based on the hybrid observer proves its efficiency in the case of sensor, parametric and discrete fault, and its high performance to detect and to localize the considered faults comparing to the other researches that already quoted in the introduction.

In the case of sensor fault, it can be seen in Fig. 9 that only the residual $r_{q \in \{1,2,3\}}^2$, corresponding to the second component of the estimated output vector h_2 , deviates from zero and therefore the fault is detected. Since its detection is done at the time $t = 1500$ s and according to the discrete automaton description, the fault is localized in the third operating mode.

In the case of the parametric fault, we observe in Fig. 11 that the residual $r_{q \in \{1,2,3\}}^2$ vary suddenly when the parameter fault occurs at $t = 1500$ s. The obtained residual signature is characterized by an overshoot. Its dynamic is different from the one obtained for the case of a sensor fault. Thus, it is possible to localize and to identify a parametric fault.

Finally, for the case of the discrete fault, we observe the evolution of the discrete automaton in Fig. 13, stopped in mode 2 and failed to proceed at mode3. Besides this one, the estimated water level $h_{i \in \{1,2,3,4\}}$ did not vary at the time $t = 1200$ s because no discrete events take place, whereas the two pumps remain operating normally. Since the valve v_3 is responsible to pass to mode 3, the faulty valve is identified at the time $t = 1200$ s.

So, the main advantage of the proposed approach based on the hybrid observer is to illustrate the importance of the switched systems modelling in order to detect its different faults whether they are a continuous or a discrete type. Several researches [24, 25] address the development of system diagnosis based on classical procedure. Its performance is limited only to detect continuous faults with a sanction of the effects of the part of the discrete events on the system functioning.

6 Conclusion

In this paper, a diagnosis method for switched linear systems is proposed and applied to a four-tank system. The proposed approach is based on a discrete automaton and a bank of Luenberger observers. The discrete automaton allows the identification of the active mode of functioning. For each mode, the synthesis of an observer is used to generate the residuals vectors in order to detect and to localize a sensor or a parametric fault. In addition, the proposed approach is suitable to detect both continuous and discrete faults. In fact, the discrete automaton is able to detect any discrete fault which can disturb the natural evolution order of the functioning modes. The obtained simulation results prove the efficiency of the proposed hybrid observer-based fault diagnosis technique. Furthermore, the proposed approach is a solution to estimate continuous state of the studied nonlinear system. Moreover, it is a reliable fault diagnosis method.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Hansen HB, Kallesoe CS, Bendtsen JD (2007) A hybrid model of a brushless DC Motor. In: IEEE international conference on control applications, Singapore, Oct 2007. <https://doi.org/10.1109/CCA.2007.4389385>
- Henzinger TA (1996) The theory of hybrid automata. In: Proceedings of 11th annual international symposium on logic in computer science. IEEE Computer Society Press, New Brunswick, pp 278–292. https://doi.org/10.1007/978-3-642-59615-5_13
- Balluchi A, Benvenuti L, Di Bernedetto MD, Sangiovanni-Vincentelli AL (2002) Design of observers for hybrid system. In: Hybrid systems: computation and control (HSCC'02), vol 2289, pp 76–89. Springer. https://doi.org/10.1007/3-540-45873-5_9
- EL Mekki A, Ben Saad K (2018) Diagnosis based on sliding mode observer for an inter-turn short circuit fault in brushless DC motors. *Revue Roumaine des Sciences Techniques- Electro-technique et Energétique* 63(4):391–396
- Gertler J (1993) Analytical redundancy methods in failure detection and isolation. *Control Theory Adv Technol* 9(1):259–285. [https://doi.org/10.1016/S1474-6670\(17\)51119-2](https://doi.org/10.1016/S1474-6670(17)51119-2)
- Iserman R (1984) Process fault diagnosis based on modeling and estimation methods: a survey. *Automatica* 20(4):387–404
- Willsky AS (1976) A survey of design methods for failure detection in dynamic systems. *Automatica* 12(6):601–611
- Patton RJ, Frank PM, Clark RN (2000) Issues of fault diagnosis for dynamic systems. Springer, Berlin
- Gara H, Ben Saad K (2018) Design of a fault detection hybrid observer for linear switched system. In 15th international multiconference on signals, systems, and devices SSD'2018, Hammamet. <https://doi.org/10.1109/SSD.2018.8570446>
- Belkhiat DEC, Manamanni N, Messai N, Djemai M (2012) Fault detection & isolation for a class of hybrid systems: a dedicated switched robust observer scheme. In: Twentieth Mediterranean and conference on control and automation (MED), pp 978–983. Barcelona. <https://doi.org/10.1109/MED.2012.6265766>
- Van Gorp J, Defoort M, Veluvolu KC, Djemai M (2015) Fault detection based on higher-order sliding mode observer for a class of switched linear systems. *IET Control Theory Appl.* <https://doi.org/10.1049/iet-cta.2014.1004>
- Yin S, Gao H, Qiu J, Kaynak O (2017) Descriptor reduced-order sliding mode observers design for switched systems with sensor and actuator faults. *Automatica* 76:282–292. <https://doi.org/10.1016/j.automatica.2016.10.025>
- Low CB, Wang D, Arogeti S, Luo M (2010) Quantitative Hybrid Bond Graph-Based Fault Detection and Isolation. *IEEE Trans Autom Sci Eng* 7(3):558–569. <https://doi.org/10.1109/TASE.2009.2024538>
- Sun J, Qin S-Y, Song Y-H (2004) Fault diagnosis of electric power systems based on fuzzy Petri nets. *IEEE Trans Power Syst* 19(4):2053–2059. <https://doi.org/10.1109/TPWRS.2004.836256>
- Bresolin D, Capiluppi M (2013) A framework for fault diagnosis of hybrid systems based on predicate abstractions. In: 2013 conference on control and fault-tolerant systems (SysTol), pp 802–807. Nice. <https://doi.org/10.1109/SysTol.2013.6693927>
- Gara H, Ben Saad K (2018) Fault detection for linear switched systems based on a bank of Luenberger observers. In: 2nd international conference on advanced systems and electrical technologies IC_ASET 2018, Hammamet. <https://doi.org/10.1109/ASET.2018.8379840>
- Hajriani P, Poshtan J (2011) Fault-tolerant tracking control for a four-tank system benchmark via eigenstructure assignment and parameter estimation. In: 2nd international conference on control, instrumentation and automation (ICCIA), Shiraz, 2011. <https://doi.org/10.1109/ICCIAutom.2011.6356709>

18. Kardos T, Kutasi DN (2017) Hybrid modeling and model based control of the four tank process. In: 6th international conference on recent achievements in mechatronics, automation, computer science and robotics, MACRo 2017. <https://doi.org/10.1515/macro-2017-0008>
19. Balluchi A, Benvenuti L, Di Bernedetto MD, Sangiovanni-Vincentelli AL (2001) A hybrid observer for the driveline dynamics. In: Proceeding 6th European control conference, ECC'2001. Porto. <https://doi.org/10.23919/ECC.2001.7075977>
20. Alessandri PC (2001) Design of Luenberger observers for a class of hybrid linear systems. In: Proceeding of hybrid systems: computation and control, Rome. https://doi.org/10.1007/3-540-45351-2_5
21. Belkhiat DEC, Messai N, Manamanni N (2011) Design of a robust fault detection-based observer for linear switched systems with external disturbances. *Nonlinear Anal Hybrid Syst* 5:206–219
22. Luenberger D (1971) An introduction to observers. *IEEE Trans Autom Control* 16:596–602
23. Huuck R, Lukoschus B, Frehse G, Engell S (2002) Compositional verification of continuous discrete system. In: Engell S, Frehse G, Schnieder E (eds) *Modeling, analysis, and design of hybrid systems*. Springer, Berlin, pp 225–244. https://doi.org/10.1007/3-540-45426-8_13
24. Youssef T, Chadli M, Karimi HR, Wang R (2017) Actuator and sensor faults estimation based on proportional integral observer for TS fuzzy model. *J Frankl Inst*. <https://doi.org/10.1016/j.jfranklin.2016.09.020>
25. Abdallah Eissa M, Darwish RR, Bassiuny AM (2019) Design of observer-based fault detection structure for unknown systems using input–output measurements: practical application to BLDC drive. *Power Electr Drive*. <https://doi.org/10.2478/pead-2019-0017>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.