Applied Mathematics & Information Sciences
An International Journal

Diagnosability of Slowly Changing Fault of Hybrid System

Zhao Jian[1,2,3,4], *Shi Lijuan*[5], *Du Qinsheng*[1,2,4] *and Wang Lirong*[1,2]

[1]College of Computer Science and Technology, Jilin University, Changchun, Jilin, 130012, P. R. China
[2]Key Laboratory of Symbolic Computation and Knowledge Engineering of Ministry of Education, Changchun, 130012, P. R. China
[3]College of Instrumentation and Electrical Engineering, Jilin University, Changchun, Jilin, 130012, P. R. China, P. R. China
[4]College of Computer Science and Technology, Changchun University, Changchun, Jilin, 130012, P. R. China
[5]College of Electronic Information and Engineering, Changchun University, Changchun, Jilin, 130012, P. R. China

Received: 16 Oct. 2012, Revised: 15 Nov. 2012, Accepted: 14 Dec. 2012
Published online: 1 Feb. 2013

Abstract: The premise of model-based diagnosis is that the system for diagnosing is diagnosable. Previous methods to diagnose fault are mainly based on the assumption of abrupt change, and under this kind of assumption, unpredictable fault can be caused by those possible slowly changing fault or that the system cannot be diagnosed. Diagnosability of slowly changing fault is discussed in this essay, and the determination method of diagnosability of slowly changing fault is put forward in the framework of hybrid input-output automata. By introducing guard event system of slowly changing fault, the diagnosing method of slowly changing fault is obtained and the feasibility of the mode is proved.

Keywords: Artificial Intelligence, Model-based Diagnosis, Diagnosability, Slowly Changing Fault, Hybrid System.

1. Introduction

The premise of model-based diagnosis is that the system for diagnosing is diagnosable. The system property expressed by this premise is diagnosability. What diagnosability guarantees is that the system can be controlled by the model-based diagnosis method and the result of the diagnosis is correct. Therefore, in the study on model-based diagnosis, study on the determination of diagnosability is usually included. Moreover, in the design of system, the requirement of diagnosability is encompassed. Studying the determination method of diagnosability under different system conditions is an important and primary step to diagnose the establishment of system and to ensure the security of follow-up system.

At present, there are two main themes for the study of diagnosability, one of which is studying the definition of diagnosability and its determination method under different system conditions and different limitations; the other is the improvement of the universally applied determination method of diagnosability.

The first theme started in 1994, the concept of diagnosability in discrete event system put forward by Feng Lin [1] in Wayne State University is adopted to strictly differ the offline working and online working of diagnosability. In 1995, setting up diagnoser offline to determine the diagnosability of the system was put forward by the researchers such as M. Sampath in University of Michigan [2], and i-diagnosability was raised by using the index event to deduce the appearance of fault; in 1996, the method was used by researchers such as M. Sampath to determine the diagnosability and to establish the diagnosing system in large HVAC system [3]. It was the method to get the most fundamental diagnosable determination in normal discrete event system. In this essay, it is pointed out that diagnosability is an important safeguard of the security and reliability of the system, which is also widely used. Till now, diagnosability starts to get the attention of researchers and experts. Research group in University of Michigan came up with more detailed theoretical analysis on diagnosability in the past twenty years. For example, in 2005, researchers such as Yin Wang [4] put forward strong diagnosability and weak diagnosability on the basis of basic diagnosability, which is used to determine the nature of the diagnosable degree and to distinguish

* Corresponding author e-mail: wanglirong.ccu@gmail.com

whether the system is normal or not, thus improving the correctness of determining the fault. Considering the uncertainty of discrete event system under actual condition, in 2005, researchers such as David Thorsley added probability to every event in the discrete event system, namely discrete event stochastic systems [5], and defined diagnosability in discrete event stochastic systems, thus resolved the determination of diagnosability under the uncertain transmission condition. In 2009, Chinese researcher Liu Fuchun [6], and Qiu Daowen put forward fuzzy diagnosability in fuzzy system according to different levels of fault. By adding membership function to all events in the system, the degree of fault can be determined by the threshold value of the event. Thus the fault can be defined and quantized and the level of diagnosability can be determined.

Different definitions of diagnosability are raised under different system conditions. According to different system behavior characteristics, different formalized definitions and determination conditions can be given to the diagnosable behavior. But the nature is still conducting searching and determining in a relatively large state space[7]. Therefore, the other main theme is to improve the efficiency of the determination of diagnosability with all kinds of methods.

At present, from the perspective of time, the best method to determine the diagnosability is polynomial in the state space of the system, while in practice, the system is very complicated. And the efficiency of overall diagnosis (the system is considered as a whole system) is very low. Bringing down the state space is an effective way to reduce the complexity. Co-research group from French Rennes University and Australian National University (Major members: Y. Pencole, M O. Cordier, A. Grastien, etc.) put forward a series of methods to accelerate the determination of diagnosability, such as the double tree method in overall system, the distributed diagnosis in the distribute system as well as decentralized diagnosis [8–10].

Method of diagnosis which is component-based divides the system into several components, and the diagnosis of the system is obtained by the diagnosis of every component. In 2000, researchers like R. Debouk from Michigan put forward the concept of common diagnosis of distributed and decentralized discrete event system. In 2006, the concept of common diagnosis was extended by Qiu Daowen so that if one part model can be diagnosed, then the diagnosable property of overall model is common diagnosis. The proposal of common diagnosis has largely improved the efficiency of determining the diagnosablility of the system, thus is widely applied. The efficiency of determining the diagnosablility in the distributed and decentralized system is improved compared with the overall situation from the perspective of order of magnitude, but the following separation of observing information may affect the determination of diagnosablility. At present, the group in Rennes University is on an in-depth study of this.

National Aeronautics and Space Administration (N A S A) has been engaged in the research of diagnoser system in the space shuttle, and has raised a determination system of two generations for static and dynamic system respectively, which are named Livingstone First Generation and Livingstone Second Generation; researchers such as Lafortune in the research group in Michigan University has been engaged in the theoretical study of diagnosis of dynamic system, and has developed the DESUMA system, which is used to determine the diagnosability of the model of automata; co-research group from French Rennes University and Australian National University (M.O.Cordier and Y.Pencole, etc.) are mainly engaged in the study on the online incremental diagnosis and distributed diagnosis and undertake the research and development of diagnosis system of French communication network; researchers such as A.Lazovik from the University of Groningen adopt the method of CSP minimizing the observable events to ensure the diagnosis of system. Professors at the S.Haar University of Toronto such as professor Wonham study the distributed diagnosis from the perspective of overall consistency.

At present, diagnosability study is conducted by MBD research group in Sun Yat-sen University and MBD research group in Jilin University in China. The MBD group in Sun Yat-sen University focuses on the MBD algorithms in static system, such as Boolean algebra method for candidate[6], binary trees hitting set methods, etc [7]; while the MBD research group in Jilin University started the MBD research in 1994. At first it focused on MBD formal method in static system. In recent years, MBD research group in Jilin University started to shift the focus of research to the dynamic system, studying the effective and correct diagnosis and determining of diagnosability in discrete event system and hybrid system under different model conditions[11].

2. Diagnosability of Slowly Changing Fault for Hybrid System

The above researching direction is mainly based on the model in the discrete event system. In hybrid system or the control system, diagnosability is usually determined by the filter. When the precision of filter is enough to distinguish the quantitative change of parameter, diagnosability of the hybrid system will be set up in the model layer rather than the physical layer.

The determining method and diagnosing method of diagnosability of hybrid system at the model level are usually based on an assumption: the occurrence of fault is in a process of abrupt change. The process either abruptly happens in the event of diversity or expresses that the continuous quantity is out of boundary. In reality, there is a kind of fault does not comply with this assumption, which is the slowly changing fault that changes with time.

Though slowly changing is not a common direction of research, it is common in reality. It can not only affect the result of diagnosis, it can also affect the conclusion of diagnosability. Take the most common three-container tank as an example. If the flowing water in the tank is not pure with some silt or metal ion, then after some time, the container of the tank, the rate of the water flow will be affected. Quality of water is not considered as a fault during of the process of setting up the model, while in reality, it is indeed a fault. The behavior itself is not a fault, but with the change of time, it will finally affect the normal operation of the system. This kind of behavior is called slowly changing fault.

Diagnosing the slowly changing fault can be taken as a promising field in the hybrid system controlling the large-scale complex system. The reason is that slowly changing fault is hard to be predicted. The difficulty lies in that it is hard to be distinguished from abrupt fault. This essay is divided into two parts. At first, the diagnosability is discussed in the discrete event system then the diagnosability of the slowly changing fault in the hybrid system is discussed, especially the diagnosability of slowly changing fault in the hybrid system on hybrid input-output automata. A method is raised to address the diagnosis of slowly changing fault in hybrid system, which can be used in hybrid system.

Fault can be classified into abrupt fault and slowly changing fault of the parameter according to its occurring and developing process. Abrupt fault is that the parameter abruptly deviates from the normal range which is random. While slowly changing fault is elusive and the parameter deviates from the normal condition gradually which ultimately leads to the obvious decrease of the performance of the system. The occurrence of slowly changing fault does not change the mode of system, but it severely affects the overall performance of system. Solving the slowly changing fault mainly focuses on how to detect the characteristic from the normal state to the state of fault, thus preventing the slowly changing fault from happening in advance. It is our work to discover the diagnosis behind the parameter, to determine which slowly changing fault is diagnosable, and how to get the result of diagnosis by reasoning.

Traditional method to diagnose the fault is based on abrupt assumption of implicit parameter. When the slowly changing fault occurs in the system, the method may have the following results: 1. Hard or unable to diagnose the slowly changing fault or the fault cannot be recognized according to the mentioned definition of fault, thus the diagnosis will not happen. 2. The diagnosis can be effectively conducted when the parameter of slowly changing fault has deviated to such degree that it has severely affected the performance of the system or one part has broken down. 3. The diagnosis is conducted in a certain range, but the result of the diagnosis is not correct.

3. Basic Concept of Slowly Changing Fault

At present, though diagnosis of slowly changing fault is not a hot research direction, it is universal and common in the real world, which affects the overall performance of system. If the fault is not diagnosed timely, it may lead to severe consequence (even abrupt fault). If the fault can be addressed at this stage and the diagnosis is given, then the great accident can be avoided which may greatly reduce the risk of system and improve the efficiency, security and stability of the system. The improvement of stability and efficiency can be called the handling method of former fault. But is different from the manifestation of the abrupt fault at prior stage, that is to say, one part of slowly changing fault can ultimately lead to abrupt change, while one part such as slowly changing fault can lead to the gradual decrease of the performance.

Take the rusting of the water pipe as example, which is not an abrupt process, but a process in which the performance gradually decreases and finally the water flow decreases. Ultimately the water pipe is blocked. If the gas of the automobile is not enough, though the automobile can normally operate, the harm to the engine is great. The former method can only enter the diagnosis when the engine is so worn that it cannot operate.

Slowly changing fault and abrupt fault can be distinguished by the classification of fault effect and the guard of slowly changing fault mentioned in this essay; because the residual of abrupt change and slowly changing fault (difference exists between the estimated value and the actual value) is different. And when slowly changing fault happens, the system will not stop but continue. But the fault will affect the overall performance and efficiency of the system while the abrupt change will not but turn to the mode of fault. Therefore, when we deal with the residual, the abrupt fault and slowly changing fault will be separated and deal with them respectively to eliminate the noise.

3.1. Overview of the System Model

The model of the whole system is built by hybrid input-output automata. We define a hybrid automaton A to describe a system. This automaton is a dynamic system including successive and discrete behavior, describing a limited set V of a changing variable, allowing shared variable and the shared behavior to share variable. In this model, the description of successive behavior of hybrid system and the discrete behavior of hybrid system can be separated (that is to say, the successive behavior and the discrete behavior are described separately).

Variables are classified. For each $\upsilon \in V$, type(υ) is used to express the type of υ. For each variable in V, that is to say, ⊆V, estimation (valuation) of is a function (equation). This function assigns every variable υ ∈Z a variable in the range of type(υ). Z is expressed as a set of valuation of Z. Usually the valuation will be raised as a state. The s∈V is used as the state of system. The valuation of variable includes both successive and discrete dynamic property.

Successive time valuation of variable in set V is described by a trace ω in the set. It is an interval mapping equation T≥0={t∈ $\Re$| t $\geq$ 0} to V. The first state of trace ω is labeled by ω. fstate, and the last state is labeled by ω .lstate.

Discrete dynamic property is coded by action. When an action happens, the system will jump into jumps, a new value. The set of action that affects the valuation of A is described by Σ

Define 1 (hybrid input output automaton): One hybrid input output automaton is defined as a system with ten unknown: $A = (U, X, Y, \Sigma_{in}, \Sigma_{out}, \Theta, D, W, \gamma)$, where:

U, X and Y, three sets of decomposition of variable are respectively called input variable set, middle variable set and output variable set. Variable set $V = U \cup X \cup Y$

$\Sigma_{in}, \Sigma_{int}$,and Σ_{out}, three sets of decomposed actions are respectively called input action set, middle action set and output action set. Set $\Sigma = \Sigma_{in} \cup \Sigma_{int} \cup \Sigma_{out}$.

–A nonempty set of original state $\Theta \subseteq V$.
–A discrete transition set $D \subseteq V \times \Sigma \times V$.
–A state reflexive set $C \subseteq V \times V$;
–A set of track on V W.

A reset function γ. Reset function γ is applicable to hybrid automation model and it can be generated by transition HBG model.

A hybrid execution α in A is an order of trace and action alternating limitedly and unlimitedly. The first state of $\alpha = \omega 0 \alpha 1 \omega 1 \alpha 2 ...$, α is an element of Θ. If α ends with a trace, then it is a limited order. If ωi is not the last trace, then its range is right closure, discretely transferring (ωi .lstate, $\alpha i+1$, $\omega i+1$) ∈D.

State reflexive set C is expressed as a state transfers to itself without any action. ωi (fstate, , statek,, ltate), slowly changing fault happens in the trace of ωi, when (ωi.statek ,ωi.statek+1) ∈C is operating in the trace.

A state s is defined as a reachable state. If a limited hybrid execution exists, then s is the last state.

3.2. Fault Modeling

Definition 2: Fault: At least a typical characteristic attribute or parameter deviates unallowably from the acceptable, normal and standard state.

According to this definition, we distinguish two different kinds of fault, namely the abrupt fault and slowly changing fault.

Definition 3: Abrupt Fault: At some time, abrupt fault is a typical characteristic attribute or system parameter deviating from the acceptable, normal, and standard condition, which is not allowed by the system. The deviation of parameter from the normal state is defined as an abrupt fault, such as the fault f can be expressed as $< p, \lambda >$. Here, p is parameter, $\lambda = \pm$indicates that the parameter deviating from the normal state.

Definition 4: Slowly changing fault. Slowly changing fault is that during a period of time, at least a typical characteristic attribute or system parameter gradually deviate from the acceptable, normal and standard condition, which is not allowed by the system behavior. The slow deviation of parameter from the normal state is defined as a slowly changing fault.

Definition 5: Mode of Fault Mode of fault is the mode that the system enters when a fault happens. Suppose there are n modes of fault F1, , Fn∈E, among which E is the set of all modes of fault. Mode of fault is divided into mode of abrupt change and mode of slowly changing fault, which are expressed as FA1FAn, FI1FIm respectively.

Definition 6: Mode of Operation. Mode of operation is an element of set O, named as the set of operation, which includes normal mode N and all the combinations of mode of fault. We suppose that there is only one mode of fault may happen for each component at one time.

We relax the restrictions form the fault and expand them to that it can not only changes the discrete state by abrupt change, but also slowly changes in the continuous state. This is our contribution.

3.3. Diagnosability of Slowly Changing Fault

According to the definition of HIOA, guard is defined as:

Definition 7(Guard): When a variable meets certain condition, the system changes from normal mode to the mode of fault by order of action. These variables are called guard, which is expressed as r, rk=yk-yk. k means the mode of k, and yk means the actual observed value of the system, and yk means the predicted value of the system.

$G = \{v \in V | (v, v) \in C, forsomev\}$ means that when the guard is met, a continuous state transferring will be activated.

Definition 8 (Guard of Slowly Changing Fault: When a variable meets a certain condition, the system turns from the normal mode to the mode of slowly changing fault, and these variables are called the guard of slowly changing fault:

G FI= $\{w \in V | (w.state, w.state) \in CFI,$
$forsomew.state\}$,

FI is the set of slowly changing fault, which means that when a variable changes to a certain degree and the system enters the mode of slowly changing fault, guard of slowly changing fault is the critical point of the system turning from the normal mode to the mode of fault.

Definition 9 Fault Trace of the Guard of Slowly Changing Fault: The fault trace is described as Ftrace(Fi), which is the smallest limited order of a trajectory and action when a fault happens, it begins with g Fi, and ends with g Fi?.

Definition 10 Mode of Fault is Distinguishable: Two modes FIi, FIj are distinguishable if their hybrid traces are different or their traces of fault are different.

Definition 11 Diagnosability of Slowly Changing Fault: One hybrid system H is diagnosable for slowly changing fault. If ?FIi , FIj ∈ E , in which FIi , FIj are distinguishable, that is to say one hybrid system H is diagnosable for slowly changing fault if two of any slowly changing fault in the mode set E of fault are distinguishable.

Definition 12 N is diagnosable: For a hybrid system H, in the diagnosing model hybrid automaton A, if any two modes of fault in the mode set E of fault of the system are distinguishable, and there are N kinds of mode in E, then H is diagnosable for N, written as: D (A, N).

Theorem 1: If any slowly changing fault in the mode of fault is distinguishable, then the corresponding hybrid system is diagnosable for slowly changing fault.

Proving: this problem is proved in two aspects, (1) Different diagnosis can be obtained by the mode of slowly changing fault, the mode of common fault and the normal mode; (2) Any two distinguishable slowly changing faults are distinguishable.

(1) There is a mode of slowly changing fault, M1. In the model, there are different prefixes of fault, which are different from other definitions of mode of fault, therefore, it can be distinguished from common mode of fault; the discrete quantity is not distinguishable if the prefix of fault is the same with that of the normal mode. From the perspective of continuous quantity, the test value got from the normal mode is different with the continuous value of slowly changing fault, therefore it is distinguishable. Therefore, no matter in the normal mode or the common mode of fault, when getting the diagnosis, it can be distinguished from the mode of slowly changing fault, therefore, it is diagnosable.

(2) There are two slowly changing faults, M1 and M2 and they are distinguishable. Then the values of M1 and M2 are not the same at the same time, and then they do not have to be in the same mode. By the definition of mode, M1 and M2 have different behavior prefixes of discrete quantity. Therefore, according to the observable discrete event and continuous quantity, different results of diagnosis can be obtained; therefore M1 and M2 are distinguishable.

By the testification and explanation of (1) and (2), it can be concluded that: if any two slowly changing faults are distinguishable, then the corresponding hybrid system is diagnosable for slowly changing fault.

4. Constructing the Diagnoser

We use a diagnoser to execute the process of diagnosis, which is a hybrid automaton, producing a signal suggesting whether the fault has happened. Its effect is to observe and detect the behavior of the automaton of the system, comparing the difference with its predicted acceptable behavior. Besides, a description of diagnosis S is produced when it detects a fault, pointing out the part of the fault and providing the information of the mode of fault to explain the reason leading to these processes of behaviors.

The fault device is passive, that is to say, it will not affect the system diagnosed, which means that supposing it is unchangeable, same observation can always lead to the same result of fault, namely the same description.

Diagnoser is composed of three parts: discrete diagnoser, continuous diagnoser and decision logic device.

Discrete diagnoser provides estimation of the discrete state of hybrid system, diagnosing the level of fault in discrete event. Continuous diagnoser provides the fault diagnosis of continuous behavior of hybrid system. And decision logic device is the final expression of the description of fault of the combination of continuous and discrete parts: $S = \cap iSDi \cap jSCj$

5. Experiment and Analysis

According to the definition of diagnosability of slowly changing fault and relevant theories, major steps of experiments are to test the diagnosability of the system.

Choosing the figure of experiment: Classical hybrid system model three-container tank is used as system model in this essay; system is composed of one pump SF1, three tanks C1, C2 and C3, three pipes R2, R3 and R4 with valves as well as two independent pipes R5 and R6. Input stream is Qf1, and output stream is QR2. Water tanks C1 and C2 are connected with pipe R5 by valve R3, and water tanks C2 and C3 are connected with R6 with R4. The output of the whole system is R2. The system has three altimetric sensors of liquid level S1H1, S2H2 and S3H3 and six Velocity sensors Qf1, QR2, QR3, QR4, QR5 and QR6.

Equation of the system:

S1H1=Qf1-QR3-QR5

S2H2=QR3+QR5-QR4-QR6

S3H3=QR6+QR4-QR2

QR3=R3(H1)-2, QR5=R5(H1')-2,

R3 and R5 are throttles. Mathematical model of the system:

S1H1=Qf1- R3(H1)-2- R5(H1')-2

S2H2= R3(H1)-2+ R5(H1')-2- R4(H2)-2- R6(H2')-2

S3H3= R4(H2)-2+ R6(H2')-2- R2(H3)-2

Input stream is Qf1, output stream is y= R2(H3)-2. Some slowly changing faults in the actual system: F1: The pipe with Sf1 rusts and the inner diameter of the pipe gradually narrows and the water yield decreases in the unit time.

The fault trace of F1 is: Qf1 → S1H1 → QR3 → QR5 F2: Water tank C1 starts to have small holes and the liquid starts to leak. The fault trace of F2 is: S1H1 → QR3 → QR5 F3: The pipe with R3 rusts and the inner diameter of the pipe gradually narrows and the water yield decreases in the unit time. The fault trace of F3 is: QR3 → S2H2 → QR4 → QR6 F4: Water tank C2 starts to have small holes and the liquid starts to leak. The fault trace of F4 is: S2H2 → QR4 → QR6 F5: The pipe with R4 rusts and the inner diameter of the pipe gradually narrows and the water yield decreases in the unit time. The fault trace of F5 is: QR4 → S3H3 → QR2 F6: Water tank C3 starts to have small holes and the liquid starts to leak. The fault trace of F6 is: S3H3 → QR2

The set of mode of fault E1= F1 , F2, F3, F4, F5, F6, according to the definition and theorem of diagnosability, because the fault trace and the hybrid trace of any two of the faults in E1 are distinguishable, hybrid system H can be diagnosed by D(A, E(6)). Suppose there is a mode of fault F7, whose fault trace is QR4 → S3H3 → QR2, and at the same time, there is a mode of fault E2= F1 , F2, F3, F4, F5, F6, F7, because the two modes of fault in E2 are the same with the fault trace of F5 and F7, the two modes of fault are not distinguishable, therefore, hybrid system H is not diagnosable in the mode set E2.

6. Conclusion

No matter for the slowly changing fault or the abrupt fault, the definition of diagnosability can be considered as: given the extent of observation and the condition of the measured value, any system characteristic that is not consistent with the predicted behavior will be obtained by the system and separated with other behaviors of the system.

Diagnosability of slowly changing fault in the hybrid system and the diagnosing method is an important issue in the monitoring of the hybrid system. The time of slowly changing fault is long, therefore at the initial stage of establishing the model it will not be considered. But in reality, this slow difference will lead to the gradual invalidation of system. And the normal behavior and the fault behavior will not be distinguished, or the detected value of the system will fluctuate around threshold. This situation is usually unavoidable in reality.

Because slowly changing fault is unavoidable in some real systems and special hybrid systems, the diagnosis of slowly changing fault and the testing method of diagnosability are paid great attention by the experts and industries. The biggest challenge lies in the complexity of the system. Besides, setting up a whole system requires not only the actual demands during the process of modeling, but also the direct and indirect cause relations among various behaviors, which urges the designers to improve the design procedures constantly.

Acknowledgement

This work was supported in part by NSFC under Grant Nos. 60973089, 60873148, 60773097, 61003101, 61133011, 61170092, 60973088; Jilin Province Science and Technology Development Plan under Grant Nos.20101501, 20100185, 20090108, 20080107, 201101039;Doctoral Fund of Ministry of Education of China (20100061110031); Opening Fund of Top Key Discipline of Computer Software and Theory in Zhejiang Provincial Colleges at Zhejiang Normal University; Zhejiang Provincial Natural Science Foundation under Grant Nos.Y1100191; Erasmus Mundus External Cooperation Window's Project (EMECW): Bridging the Gap, 155776 -EM -1 -2009 -1 -IT -ERAMUNDUS -ECW -L12. The Opening Foundation of Key Laboratory of Symbolic Computation and Knowledge Engineering of Ministry of Education underGrant No.93K- 17 -2009 -K05.

References

[1] F. Lin, Discrete Event Dynamic systems,197-212 (1994).
[2] M. Sampath, R. Sengupta, S. Lafortune, K. Sinnamohideen and D. Teneketzis, IEEE Trans. Automatic Control, 1555-1575 (1995).
[3] Meera Sampath, Raja Sengupta, Stephane Lafortun etc, IEEE Transactions on Control Systems Technology, 105-124 (1996).
[4] Yin Wang, Tae-Sic Yoo and Stephane Lafortune, The 44th IEEE Conference on Decision and Control, and European Control Conference, Seville, Spain, (2005).
[5] Thorsley D, Teneketzis D, IEEE Transactions on Automatic Control, 476-492 (2005).
[6] Fuchun Liu, Daowen Qiu. Diagnosability of Fuzzy Discrete-Event Systems: A Fuzzy Approach[J]. IEEE TRANSACTIONS ON FUZZY SYSTEMS, 372-384 (2009).
[7] Xibin Zhao, Applied Mathematcs and Information Sciences (AMIS), Volume **6**, No. 2, 345-356 (2012).
[8] Bourgne, G, Dague, P, Nouioua, F,Rapin, 2009 First International Conference on Advances in System Testing and Validation Lifecycle, 147-154 (2009).
[9] Pencol, Yannick, 17th IEEE International Conference on Tools with Artificial Intelligence, ICTAI'05, 549-556 (2005).
[10] Marie-Odile Cordier, Yannick Pencol, Louise Trav-Massuys, and Thierry Vidal, In Proc. 18th International Workshop on Principles of Diagnosis, (2007).
[11] Zhang Li-Ming, Ouyang Dan-Tong, Zhao Jian and Bai Hong-Tao, Applied Mathematics and Information Sciences (AMIS), No. 6-1S, 119-122 (2012).

Zhao Jian received the MS degree in Computer science and Technology from JiLin University in 2008, and the PhD degree in Computer science and Technology from the department of Computer science and Technology, JiLin University in 2012. His research interests are in the areas of Artificial Intelligence, Model-based Diagnosis and Hybrid System.

Shi Lijuan received her MS degree in Detection Technology and Automation Devices from Changchun University of Science and Technology in 2009. Her research interests are in the areas of Artificial Intelligence, Pattern Recognition and Intelligent Control.