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Towards timed fuzzy Petri net algorithms for chemical abnormality monitoring

Zhenjuan Liu, Hongguang Li *, Peijian Zhou

Automation Department, Beijing University of Chemical Technology, Beijing 100029, China

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ABSTRACT

One critical problem in the operations of chemical processes is the occurrence of abnormal events. Therefore, an effective process monitoring methodology that can help detect, diagnose and predict abnormal events becomes potentially very useful. For the purpose of knowledge representation of chemical abnormality, a specified type of timed fuzzy Petri net (tFPN) approach is explicitly introduced in this paper. The dominant feature of tFPN metrics can be recognized from the fact that a timing factor is assigned to each transition, as well as a degree of reliability is associated with each place, which allows accurately representing the dynamic nature of fuzzy knowledge pertaining to abnormal events. Following a procedure towards abnormal event monitoring, two efficient algorithms in terms of abnormality prognostication and diagnosis are exploited by means of reachability analysis of tFPN. The benefits of derived techniques and solutions are illustrated through a case study consisting in a polypropylene reactor.

1. Introduction

In chemical engineering practice, abnormal event monitoring is driven by increasing concerns for diagnosing faults, ensuring safe and smooth operations. Abnormality of varying magnitudes could result in incipient faults, near-misses, incidents, or even forced shutdown of plants. In recent years, fault diagnosis of chemical process has become an active area in both academia and industry. Whereas, monitoring of abnormal events in terms of predicting consequences, compensating and correcting abnormal situations has found only a limited reports.

Generally speaking, abnormal event is referred to as a departure from an admissible range of an observed variable or a calculated parameter associated with a process. Failures in equipments may cause abnormalities, while mal-operations and larger process disturbances may also give rise to them. Thus, in realistic production environment, it is usually difficult for operators to identify the causes of abnormal events so as to achieve effective solutions in time.

Incorporating fuzzy philosophy in Petri net, fuzzy Petri net (FPN) is acknowledged to have inherited the key advantages of both graphical power and fuzzy reasoning capability, which has been extensively studied and widely circulated in the literature (Bugarn & Barro, 1994; Cao & Sanderson, 1995; Chen, Ke, & Chang, 1990; Garg, Ahson, & Gupta, 1991). Nevertheless, employed as a tool to handle dynamic knowledge pertaining to abnormal events, FPN still suffers a couple of deficiencies, such as:

- Difficulty in describing sharing behavior of abnormality propagation: in FPN model, token is regarded as a flow resource moved with fuzzy inferring. As a consequence, the firing of transition leads to not only occurrence of subsequent symptoms but also disappearance of the former, which is not in accordance with the mechanism of abnormality evolutions.
- Difficulty in describing temporal behavior of abnormality evolution: owing to the intrinsic dynamic nature of chemical process, abnormal event always travels with time going on. However, temporal factor appears nowhere in the structure of conventional FPN.

Several approaches have been presented to modify FPN in knowledge representations. For instance, when fuzzy Petri net is used to model production rule, flow of token is regarded as generation other than consumption of resources. To address this issue, Nazareth (1993) suggested that, when output places capture new tokens, the tokens in input places should keep unchanged and a control place should be additionally added to each transition to prevent transition being fired endless. Pedrycz and Camargo (2003) provided a kind of timed extension of fuzzy Petri nets by means of associating temporal fuzzy sets to either transitions or places. Thus, the influence of time factor on performance of Petri net can be recognized. In addition, a type of fuzzy timed Petri net model was introduced and successively investigated by Ding et al. (2005) and Ding et al. (2006). In their studies, each transition is associated with a fuzzy number representing the firing time, and each place is provided with a time dependent mark distribution function. In order to represent dynamic knowledge, a termed adaptive fuzzy Petri net was initially proposed by Li and Lara-Rosano

* Corresponding author. Tel.: +86 10 64434797; fax: +86 10 64442932.
E-mail address: lihg@mail.buct.edu.cn (H. Li).

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(2000) and further investigated by Chiang, Tai, and Hou (2009), which is identified to have both the features of a fuzzy Petri net and learning ability of a neural network. Nevertheless, to the best of our knowledge, industrial relevance of the fuzzy Petri nets with characteristics of dynamic knowledge representation has scarcely circulated in the literature ever since.

Motivated by effectively describing incipient abnormality evolution in chemical process, a novel temporal version of fuzzy Petri net, designated timed fuzzy Petri Net (tFPN), is presented in this paper. With emphasis on fuzzy knowledge representation, the input and output places of each transition are used to describe the antecedent and consequent propositions of the fuzzy production rules, respectively. Additionally, a timing factor is assigned to each transition and a degree of reliability is associated with each place to capture the dynamic nature of abnormality, which allows the automatic inference of reliability and undergoing time of abnormal events. After that, together with a procedure towards abnormal event monitoring, two efficient algorithms in regard to abnormality prognostication and diagnosis are exploited by employing reachability analysis of tFPN. The benefits of the derived techniques and solutions are illustrated through a case study consisting in a polypropylene reactor.

The paper is organized as follows. In Section 2, some definitions related with tFPN are highlighted, together with schemes of tFPN based knowledge representations. This is followed in Section 3 by dealing with some crucial issues of abnormal event monitoring, including analysis of abnormal event evolution, as well as the diagnostic and prognostic inference algorithms. Section 4 contains a case study that helps exemplify the proposed techniques. Section 5 concludes the paper and discusses areas for future work.

2. Preliminaries

2.1. Definitions of timed fuzzy Petri nets

Definition 1. A timed fuzzy Petri net is a tuple:

$tFPN = (P, T, E, I, O, f, \alpha, \beta, D, TS, M_0)$,

where

$P = \{p_1, p_2, \ldots, p_n\}$ denotes a finite set of places;
$T = \{t_1, t_2, \ldots, t_n\}$ denotes a finite set of transitions, where $P \cap T = \Phi$;
$E = \{e_1, e_2, \ldots, e_n\}$ denotes a finite set of propositions, where $|P| = |E|$;
$I{:}P \times T \to \{0,1\}$ is an input function, representing a mapping from input places to transitions;
$O{:}T \times P \to \{0,1\}$ is an output function, representing a mapping from transitions to output places;
$f{:}T \to [0,1]$ is a relationship function with respect to transition t, representing a mapping from t to a real number confined in [0,1];
$\alpha{:}P \to [0,1]$ is a relationship function with respect to place p, representing a mapping from p to a real number bounded in [0,1];
$\beta{:}P \to E$ is a relationship function with respect to place p, representing a bidirectional mapping between p and the proposition set;
$D = \{d_1, d_2, \ldots, d_n\}$, $C(T) \to R^+$, is a time delay function associated with each transition;
TS is a finite set of transition states, $\forall TS_i \in TS$, $TS_i \in \{0,1\}$; $TS_i = 1$ implies that the corresponding transition t_i has been fired, otherwise,$TS_i = 0$ implies that t_i has not been fired;
$M_0$is an initial marking, $\forall m_i \in M_0, m_i \in \{0,1\}$.

Definition 2. An enabled transition should satisfy following preconditions:

(1) $\forall t_i \in T, TS_i \notin TS$ implies that the transition has not been fired;
(2) Let m_1 and m_2, respectively, are the markings at time τ_0 and $\tau(\tau_0 + d_i = \tau)$. For the transition t_i and the marking m_1, there is $\forall p_j \in I(t_i),\ m_1(p_j) = 1 \wedge \alpha(p_j) = y_i \geqslant \lambda_i$, where $\lambda_i \in [0,1]$ is the threshold of t_i, and $m_1(p_j)$ is the reliability ofp_j.

Definition 3. If transition t_j is fired, the markings of the input places and output places will be altered at the time τ, satisfying follows:

(1) $\forall p_j \in I(t_i)$, $m_2(p_j) = m_1(p_j)$;
(2) $\forall p_k \in O(t_i)$, $m_2(p_k) = m_1(p_k) + 1 \wedge \alpha(p_k) = y_j \times \mu_i$, $\mu_i = f(t_i)$ is the transition function of t_i;
(3) The state marking of transition t_i remains $TS_i = 1$;
(4) If there is $\forall p_k \in O(t_i), m_2(p_k) \geqslant \lambda_k$, a token is added in the output place p_k.

2.2. tFPN representations for fuzzy rules

With a strong ability of knowledge representations, fuzzy Petri net has an increasing popularity in providing a couple of attractive advantages (Lee, Liu, & Chiang, 1998), such as:

- Helping construct and modify fuzzy rules with graphical representation.
- Capturing dynamic nature of fuzzy rule-based reasoning with marking evaluation.
- Improving efficiency of fuzzy rule-based reasoning with net-based structure.
- Allowing checking properties of modeled systems with analytic capability.

As a temporal extension of FPN, the tFPN approach is oriented to represent a kind of temporal deductive fuzzy rule typically stated in the following form:

R_i : IF e_j THEN e_k with μ_i and d_i

where $\mu_i \in [0,1]$ corresponds to the fuzzy reliability of the proposition, and $d_i \in R$ is the time delay associated with the deduction. Fig. 1 shows the tFPN representation of R_i, along with corresponding deductive reference, where y_j denotes the reliability of p_j, and λ_k denotes the reliability threshold for firing t_i.

Based on this principle, the conjunctive and disjunctive temporal fuzzy rules together with reference processes, respectively, are mapped using tFPN metrics as described in Figs. 2 and 3.

3. Methodologies

The major tasks involved in abnormal event monitoring can be categorized into two aspects:

(1) *Diagnosis*: find the underlying causes of abnormal events, including disturbances stemmed from process operations or hard failures in equipments; and
(2) *Prognostication*: analyze the evolutions of abnormal events and forecast the possible consequences.

As we know, reachability analysis is a potentially useful tool particularly in Petri net application issues. With respect to tFPN, it may offer an opportunity to find a possible firing sequence acquiring a maximum reliability for the target marking, as well