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模糊离散事件系统基于验证器的模式故障诊断

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摘 要: 针对模糊系统在运行过程中可能出现由多个事件触发的故障,研究模糊离散事件系统模式故障的诊断问题,提出一种基于验证器的模式故障诊断方法. 先对模糊离散事件系统中最常见的模式故障,引入S类型模式故障和T类型模式故障两个概念,再分别对模糊离散事件系统的S类型和T类型模式故障的可诊断性进行形式化. 为验证模糊系统模式故障的可诊断性,构造一个验证器自动机,并得到一个关于模糊离散事件系统模式故障可诊断性的充分必要条件,实现对模糊系统模式故障的诊断.

关键词: 模糊离散事件系统；故障诊断；模式故障；验证器自动机

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Verifier-based pattern diagnosis of fuzzy discrete-event system

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Abstract: In this paper, the diagnosability of patterns failures of fuzzy discrete-event systems (FDES) is investigated, where patterns failures may be triggered by sequences of events during system operations, and a verifier-based pattern diagnosis approach is proposed. Firstly, the notions of S-type pattern failure and T-type pattern failure are introduced in fuzzy systems. Then the diagnosability of S-type pattern failures and the T-types pattern failures of the FEDS are formalized. In order to verify the diagnosability of pattern failures of the FDES, a verifier automaton is constructed, and a sufficient and necessary condition for the diagnosability of pattern failures is presented.

Keywords: fuzzy discrete-event systems；failures diagnosis；pattern failures；verifier automaton

0 引 言

离散事件系统(discrete-event systems, DES)为离散事件按照一定运行规则相互作用而触发状态演化的一类动态系统,在安全领域有着广泛应用,离散事件系统的故障诊断问题近年来也成为了国内外学者的研究热点[1-4].

模糊控制是一种研究不确定问题的有效方法. 由日本科学家Takagi和Sugeno提出的T-S (Takagi-Sugeno)模糊系统有着广泛应用,例如文献[5]对离散时间T-S模糊系统提出了一种多瞬时观测器的设计方法和一种宽松实时调度稳定性分析方法. 在DES方面, Lin等[6]将经典DES模型与模糊集理论相结合,提出了模糊离散事件系统(fuzzy discrete-event systems, FDES)概念,在生物医学领域、机器人控制等领域得到了成功应用[7-8]. 随后, FDES的许多理论得到了迅速发展. 譬如文献[9]和文献[10]从系统事件可观察性和可控性角度研究了FDES的监督控制问题: 文献[9]系统建立了集中式和分散式的FDES监督控制; 文献[10]系统建立了分布式的FDES监督控制,其中系统事件集有着明确的可观察性和可控性. Liu等也从不同的角度对FDES进行了深入研究,比如在可诊断性方面,提出了一种FDES的故障诊断方法[11]; 在分布式系统方面,提出了一个复杂度为多项式时间的分布式FDES验证算法[12]; 在安全诊断方面,提出了一种FDES的安全故障诊断算法[13].

上述FDES故障诊断方法都只是考虑了仅由单个事件(即故障事件)引起的故障诊断问题,在现实系统中,故障往往是由多个事件组成的事件串(称为模式故障). 近年来,模式故障也引起了许多学者的关注. 文献[14]将经典DES故障诊断扩展到经典DES

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的模式故障诊断,提出了系统可诊断性的验证算法;文献[15]将离散事件系统的模式故障诊断应用到自然语言的语义模式识别中,得到了一种语义模式特征提取和识别方法.

本文针对模糊系统的模式故障,研究FDES的模式故障诊断问题,提出一种基于验证器的模式故障诊断方法,并构造一个验证器自动机,得到一个关于FDES模式故障可诊断性的充分必要条件,实现对模糊系统模式故障的诊断.

1 模糊离散事件系统(FDES)

一个离散事件系统可以用非确定型有限状态自动机$G = (X, \Sigma, \delta, x_0, F)$表示. 其中: X为有限状态集合; x_0为系统初始状态; Σ为事件集合,可分为可观事件集Σ_o和不可观事件集Σ_{uo},即$\Sigma = \Sigma_o \bigcup \Sigma_{uo}$,记$\Sigma^*$为$\Sigma$中所有有限长事件串的集合,包含了空串$\varepsilon$; δ为状态转移函数$\delta : X \times \Sigma \to 2^X$, $F \subseteq X$为标记状态集合.

对于任意事件串s,如果$s = utv,\ u, t, v \in \Sigma^*$,则称$u$为$s$的前缀, t为s的子串, v为s的后缀. s的子序列为s中除去0个或多个事件得到的事件串,用$|s|$表示s的长度.

在FDES中的模糊状态定义为一个n维向量$\tilde{q} = \{a_0, a_1, \ldots, a_{n-1}\}$,其中$a_i \in [0, 1]$表示系统的当前状态为$q_i$的可能性. 类似地,在FDES中的模糊事件定义为一个$n \times n$矩阵$\sigma = [a_{ij}]_{n\times n}$,其中$a_{ij} \in [0, 1]$表示当事件$\tilde{\sigma}$发生时系统从状态$q_i$转移到状态$q_j$的可能性.

定义1 FDES是一个max-min系统,有

$$\tilde{G} = (\tilde{Q}, \tilde{\Sigma}, \tilde{\delta}, \tilde{q}_0, \tilde{F}). \tag{1}$$

其中: $\tilde{Q}$表示模糊状态集, $\tilde{\Sigma}$表示模糊事件集, $\tilde{q}_0$表示初始模糊状态, $\tilde{F}$表示被标记的模糊状态集,状态转移函数$\tilde{\delta} : \tilde{Q} \times \tilde{\Sigma} \to \tilde{Q}$定义为$\tilde{\delta}(\tilde{q}, \tilde{\sigma}) = \tilde{q} \odot \tilde{\sigma}$. 符号$\odot$为最大-最小运算: 对于矩阵$A = [a_{ij}]_{n\times m}$和矩阵$B = [b_{ij}]_{m\times k}$,有$A \odot B = [c_{ij}]_{n\times k}$,其中

$$c_{ij} = \max_{l=1}^{m} \min\{a_{il}, b_{lj}\}. \tag{2}$$

2 模糊离散事件系统的模式故障可诊断性

设$\tilde{G} = (\tilde{Q}, \tilde{\Sigma}, \tilde{\delta}, \tilde{q}_0, \tilde{F})$为一个FDES,引入3个模糊子集函数: 不可观模糊事件子集函数$\tilde{E}_{uo} : \tilde{\Sigma} \to [0, 1]$,可观模糊事件子集函数$\tilde{E}_o : \tilde{\Sigma} \to [0, 1]$和模糊事件隶属于模式故障$\tilde{K}$的子集函数$\tilde{E}_{\tilde{K}} : \tilde{\Sigma} \to [0, 1]$,其中$\tilde{K}$为模式故障集. $\tilde{E}_{uo}(\tilde{\sigma})$和$\tilde{E}_o(\tilde{\sigma})$为模糊事件$\tilde{\sigma}$的可观察的程度,满足

$$\tilde{E}_{uo}(\tilde{\sigma}) + \tilde{E}_o(\tilde{\sigma}) = 1. \tag{3}$$

而$\tilde{E}_{\tilde{K}}(\tilde{\sigma})$代表事件$\tilde{\sigma}$在$\tilde{K}$中发生的可能性大小. 同时,对于模糊事件串$\tilde{\sigma}_1\tilde{\sigma}_2 \ldots \tilde{\sigma}_m$,定义

$$\tilde{E}_o(\tilde{\sigma}_1\tilde{\sigma}_2 \ldots \tilde{\sigma}_m) = \min\{\tilde{E}_o(\tilde{\sigma}_i) : i = 1, 2, \ldots, m\};$$
$$\tilde{E}_M(\tilde{\sigma}_1\tilde{\sigma}_2 \ldots \tilde{\sigma}_m) = \max\{\tilde{E}_o(\tilde{\sigma}_i) : i = 1, 2, \ldots, m\};$$
$$\tilde{E}_{\tilde{K}}(\tilde{\sigma}_1\tilde{\sigma}_2 \ldots \tilde{\sigma}_m) = \min\{\tilde{E}_{\tilde{K}}(\tilde{\sigma}_i) : i = 1, 2, \cdots, m\}.$$

为避免下文中所构造诊断器的事件集为空集,定义$\tilde{\Sigma}_{\max\text{-}o}$为可观程度最大的模糊事件子集. 引入以下符号: 语言$\tilde{L}$是指$\tilde{G}$的生成语言,有

$$\tilde{L} = \{\tilde{s} \in \tilde{\Sigma}^* | (\exists \tilde{q} \in \tilde{Q})\tilde{\delta}(\tilde{q}_o, \tilde{s}) = \tilde{q}\}; \tag{4}$$

事件串$\tilde{s}$的后缀集定义为

$$\tilde{L}/\tilde{s} = \{\tilde{t} \in \tilde{\Sigma}^* | (\exists \tilde{q} \in \tilde{Q})\tilde{\delta}(\tilde{q}_o, \tilde{s}\tilde{t}) = \tilde{q}\}; \tag{5}$$

关于模糊事件$\tilde{\sigma} \in \tilde{\Sigma}$的可观事件集定义为

$$\tilde{\Sigma}_{\tilde{\sigma}} = \tilde{\Sigma}_{\max\text{-}o} \bigcup \{\tilde{a} \in \tilde{\Sigma} | \tilde{E}_o(\tilde{a}) \geqslant \tilde{E}_o(\tilde{\sigma})\}. \tag{6}$$

定义2 给定模糊事件$\tilde{\sigma} \in \tilde{\Sigma}$,映射函数$P_{\tilde{\sigma}} : \tilde{\Sigma} \to \tilde{\Sigma}_{\tilde{\sigma}}$定义为

$$P_{\tilde{\sigma}}(\tilde{a}) = \begin{cases} \tilde{a},\ \tilde{a} \in \tilde{\Sigma}_{\max\text{-}o} \text{ or } \tilde{a} \in \tilde{\Sigma}_{\tilde{\sigma}}; \\ \varepsilon,\ \text{otherwise}. \end{cases} \tag{7}$$

满足递归$P_{\tilde{\sigma}}(\varepsilon) = \varepsilon$且$P_{\tilde{\sigma}}(\tilde{s}\tilde{a}) = P_{\tilde{\sigma}}(\tilde{s})P_{\tilde{\sigma}}(\tilde{a})$,其中$\tilde{a} \in \tilde{\Sigma}, \tilde{s} \in \tilde{\Sigma}^*$. 反映射$P_{\tilde{\sigma}}^{-1}(\tilde{q})$定义为

$$P_{\tilde{\sigma}}^{-1}(\tilde{q}) = \{\tilde{s} \in \tilde{\Sigma}^* | (\exists \tilde{q} \in \tilde{Q})\tilde{\delta}(\tilde{q}_0, \tilde{s}) \bigwedge P_{\tilde{\sigma}}(\tilde{s}) = \tilde{q}\}.$$

记$\tilde{\Sigma}^*_{\text{pat}} = \{\tilde{u} \in \tilde{\Sigma}^* | \tilde{E}_{\tilde{K}}(\tilde{u}) > 0\}$, $\tilde{K}$为有限长度模糊事件串组成的模式故障集. 对于$\tilde{s} \in \tilde{\Sigma}^*_{\text{pat}}$,模式故障$\tilde{K}$发生S类型和T类型模式故障的可能性分别定义为

$$\tilde{E}^{\tilde{S}}_{\tilde{K}}(\tilde{s}) = \{\tilde{E}_{\tilde{K}}(\tilde{u}) | \tilde{u} \in \tilde{\Sigma}^*_{\tilde{\text{pat}}},\ \tilde{u}\text{是}\tilde{s}\text{的子序列}\},$$
$$\tilde{E}^{\tilde{T}}_{\tilde{K}}(\tilde{s}) = \{\tilde{E}_{\tilde{K}}(\tilde{u}) | \tilde{u} \in \tilde{\Sigma}^*_{\tilde{\text{pat}}},\ \tilde{u}\text{是}\tilde{s}\text{的子串}\}.$$

对于$\tilde{k}\tilde{\sigma} \in \tilde{\Sigma}^*_{\text{pat}}, \tilde{u} \in \tilde{K} \subseteq \tilde{\Sigma}^*_{\text{pat}}$,有

$$\tilde{S} = \{\tilde{s} \in \tilde{L} | \tilde{k}\tilde{\sigma}\text{是}\tilde{s}\text{的子序列}\}, \tag{8}$$
$$\tilde{T} = \{\tilde{s} \in \tilde{L} | \tilde{k}\tilde{\sigma}\text{是}\tilde{s}\text{的子串}\}. \tag{9}$$

$\Psi_{\tilde{S}}(\tilde{K})$表示以$\tilde{K}$模式故障的子序列结尾的事件串,即

$$\Psi_{\tilde{S}}(\tilde{K}) = \{\tilde{s}\tilde{\sigma} \in \tilde{S} | \tilde{k}\tilde{\sigma}\text{是}\tilde{s}\tilde{\sigma}\text{的子序列}\} \bigwedge \{\tilde{E}^{\tilde{S}}_{\tilde{K}}(\tilde{s}\tilde{\sigma}) \geqslant \tilde{E}_{\tilde{K}}(\tilde{u})\}. \tag{10}$$

$\Psi_{\tilde{T}}(\tilde{K})$表示以$\tilde{K}$模式故障的子串结尾的事件串,即

$$\Psi_{\tilde{T}}(\tilde{K}) = \{\tilde{s}\tilde{\sigma} \in \tilde{T} | \tilde{k}\tilde{\sigma}\text{是}\tilde{s}\tilde{\sigma}\text{的子串}\} \bigwedge \{\tilde{E}^{\tilde{T}}_{\tilde{K}}(\tilde{s}\tilde{\sigma}) \geqslant \tilde{E}_{\tilde{K}}(\tilde{u})\}. \tag{11}$$

定义3 给定$\tilde{u} \in \tilde{K} \subseteq \tilde{\Sigma}^*_{\text{pat}}, \tilde{\sigma} \in \tilde{u}$,其中$\tilde{\sigma}$满足条件$\tilde{E}_o(\tilde{\sigma}) \in (\tilde{E}_o(\tilde{u}), \tilde{E}_M(\tilde{u})]$, S类型模式模糊诊断函数定义为

$$\mathrm{FD}_{\tilde{K}}^{\tilde{S}}:\tilde{\Sigma}^{*}\to[0,1]. \quad (12)$$

其中:对于$\tilde{s}\in\Psi_{\tilde{S}}\{\tilde{K}\},\tilde{t}\in\tilde{L}/\tilde{s}$,有

$$\mathrm{FD}_{\tilde{K}}^{\tilde{S}}(\tilde{s}\tilde{t})=\max_{\tilde{u}\in\tilde{K}}\Big\{\frac{D}{\tilde{E}_{\tilde{K}}(\tilde{u})}\Big\},$$

$$D=\min\{\tilde{E}_{\tilde{K}}(\tilde{u}),\tilde{E}_{\tilde{K}}^{\tilde{S}}(\tilde{\omega})|\tilde{\omega}\in P_{\tilde{\sigma}}^{-1}P_{\tilde{\sigma}}(\tilde{s}\tilde{t})\subseteq\tilde{S}\}.$$

定义4　给定$\tilde{u}\in\tilde{K}\subseteq\tilde{\Sigma}_{\mathrm{pat}}^{*},\tilde{\sigma}\in\tilde{u}$,其中$\tilde{\sigma}$满足条件$\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})]$,T类型模式模糊诊断函数有如下定义:

$$\mathrm{FD}_{\tilde{K}}^{\tilde{T}}:\tilde{\Sigma}^{*}\to[0,1]. \quad (13)$$

给定$\tilde{s}\in\Psi_{\tilde{T}}\{\tilde{K}\}$且$\tilde{t}\in\tilde{L}/\tilde{s}$,则

$$\mathrm{FD}_{\tilde{K}}^{\tilde{T}}(\tilde{s}\tilde{t})=\max_{\tilde{u}\in\tilde{K}}\Big\{\frac{D}{\tilde{E}_{\tilde{K}}(\tilde{u})}\Big\},$$

$$D=\min\{\tilde{E}_{\tilde{K}}(\tilde{u}),\tilde{E}_{\tilde{K}}^{\tilde{T}}(\tilde{\omega})|\tilde{\omega}\in P_{\tilde{\sigma}}^{-1}P_{\tilde{\sigma}}(\tilde{s}\tilde{t})\subseteq\tilde{T}\}.$$

定义5　$\tilde{G}=(\tilde{Q},\tilde{\Sigma},\tilde{\delta},\tilde{q}_0,\tilde{F})$为一个FDES, $\tilde{L}$为由$\tilde{G}$生成的语言. 给定$\tilde{K}\subseteq\tilde{\Sigma}_{\mathrm{pat}}^{*},\tilde{u}\in\tilde{K}$和$\tilde{\sigma}\in\tilde{u}(\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})])$,如果满足

$$(\exists n\in\boldsymbol{N})(\forall\tilde{s}\in\Psi_{\tilde{S}}(\tilde{K}))(\forall\tilde{t}\in\tilde{L}/\tilde{s})(|\tilde{t}|\geqslant\tilde{n}\Rightarrow \min_{\tilde{K}}(\mathrm{FD}_{\tilde{K}}^{\tilde{S}}(\tilde{s}\tilde{t}))=\lambda), \quad (14)$$

则称系统$\tilde{G}$为程度是λ的S类型模式可诊断,其中$\lambda\in[0,1]$.

定义6　$\tilde{G}=(\tilde{Q},\tilde{\Sigma},\tilde{\delta},\tilde{q}_0,\tilde{F})$为一个FDES, $\tilde{L}$为由$\tilde{G}$生成的语言. 给定$\tilde{K}\subseteq\tilde{\Sigma}_{\mathrm{pat}}^{*},\tilde{u}\in\tilde{K}$和$\tilde{\sigma}\in\tilde{u}(\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})])$,如果满足

$$(\exists n\in\boldsymbol{N})(\forall\tilde{s}\in\Psi_{\tilde{T}}(\tilde{K}))(\forall\tilde{t}\in\tilde{L}/\tilde{s})(|\tilde{t}|\geqslant\tilde{n}\Rightarrow \min_{\tilde{K}}(\mathrm{FD}_{\tilde{K}}^{\tilde{T}}(\tilde{s}\tilde{t}))=\lambda), \quad (15)$$

则称系统$\tilde{G}$为程度是λ的T类型模式可诊断,其中$\lambda\in[0,1]$.

3　FDES模式可诊断性验证器的构造

设$\tilde{K}\subseteq\tilde{\Sigma}_{\mathrm{pat}}^{*},\tilde{u}\in\tilde{K},\tilde{\sigma}\in\tilde{u}(\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})])$,引入符号

$$\Delta=\{\tilde{F}_{\tilde{D}}^{\gamma}:\gamma=\tilde{E}_{\tilde{K}}(\tilde{s}),\tilde{s}\in\tilde{D}\}\bigcup \{N^{\mu}:\mu=\tilde{E}_{\tilde{K}}(\tilde{\sigma}),\tilde{\sigma}\in\tilde{\Sigma}\}. \quad (16)$$

其中: N^{μ}表示事件$\tilde{\sigma}\in\tilde{\Sigma}$的$\tilde{K}$模式故障发生可能性的大小为$\mu$; $\tilde{F}_{\tilde{D}}^{\gamma}$表示模糊事件串$\tilde{s}$发生$\tilde{K}$模式故障的可能性大小为$\gamma$, $\tilde{D}\in\{\tilde{S},\tilde{T}\}$.

给定模糊事件集$\tilde{\Sigma},\tilde{u}\in\tilde{K}$和一个模糊事件串$\tilde{s}=\tilde{\sigma}_1\tilde{\sigma}_2\dots\tilde{\sigma}_m\in\tilde{\Sigma}_{\mathrm{pat}}^{*}$,构建一个FDES为

$$\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})=(\tilde{Q}_{\tilde{S}},\tilde{\Sigma},\tilde{\delta}_{\tilde{S}},\tilde{q}_0^{\tilde{S}},\tilde{F}_{\tilde{S}}). \quad (17)$$

其中

$$\tilde{Q}_{\tilde{S}}=\{(0,l_0),(1,l_1),\dots,(|\tilde{s}|,l_{|\tilde{s}|})\},$$
$$\tilde{q}_0^{\tilde{S}}=(0,l_0),\ \tilde{F}_{\tilde{S}}=\{(|\tilde{s}|,l_{|\tilde{s}|})\},$$
$$l_i\in\Delta,\ i=0,1,\dots,|\tilde{s}|.$$

设$\tilde{q}\in\tilde{Q}_{\tilde{S}}/\{(|\tilde{s}|,l_{|\tilde{s}|})\},\tilde{\sigma}\in\tilde{\Sigma}$,有

$$\tilde{\delta}_{\tilde{S}}(\tilde{q},\tilde{\sigma})=\tilde{\delta}_{\tilde{S}}((\alpha,l_\alpha),\tilde{\sigma})=\begin{cases}((\alpha+1),l_{\alpha+1}),\\ (\tilde{\sigma}=\tilde{\sigma}_{\alpha+1})(l_\alpha\geqslant l_{\alpha+1})((\alpha+1)<|\tilde{s}|);\\ ((\alpha+1),l_\alpha),\\ (\tilde{\sigma}=\tilde{\sigma}_{\alpha+1})(l_\alpha<l_{\alpha+1})((\alpha+1)<|\tilde{s}|);\\ ((\alpha+1),\tilde{F}_{\tilde{S}}^{\gamma}),\ (\tilde{\sigma}=\tilde{\sigma}_{\alpha+1})((\alpha+1)=|\tilde{s}|);\\ (\alpha,l_\alpha),\ \text{otherwise}.\end{cases}$$

其中$\alpha=1,2,\dots,|\tilde{s}|-1$;

$$\gamma=\begin{cases}1+\tilde{E}_{\tilde{K}}^{\tilde{S}}(\tilde{s}),\ \tilde{E}_{\tilde{K}}^{\tilde{S}}(\tilde{s})\geqslant\tilde{E}_{\tilde{K}}(\tilde{u});\\ \tilde{E}_{\tilde{K}}^{\tilde{S}}(\tilde{s}),\ \tilde{E}_{\tilde{K}}^{\tilde{S}}(\tilde{s})<\tilde{E}_{\tilde{K}}(\tilde{u});\end{cases}$$

$$\tilde{\delta}_{\tilde{S}}((|\tilde{s}|,\tilde{F}_{\tilde{S}}^{\gamma}),\tilde{\sigma})=(|\tilde{s}|,\tilde{F}_{\tilde{S}}^{\gamma}).$$

给定一个模糊事件集$\tilde{\Sigma},\tilde{u}\in\tilde{K}$和一个模糊事件串$\tilde{t}=\tilde{\sigma}_1\tilde{\sigma}_2\dots\tilde{\sigma}_n\in\tilde{\Sigma}_{\mathrm{pat}}^{*}$,构建另一个FDES为

$$\tilde{H}_{\tilde{T}}(\tilde{\Sigma},\tilde{t})=(\tilde{Q}_{\tilde{T}},\tilde{\Sigma},\tilde{\delta}_{\tilde{T}},\tilde{q}_0^{\tilde{T}},\tilde{F}_{\tilde{T}}). \quad (18)$$

其中

$$\tilde{Q}_{\tilde{T}}=\{(0,l_0),(1,l_1),\dots,(|\tilde{t}|,l_{|\tilde{t}|})\},$$
$$\tilde{q}_0^{\tilde{T}}=(0,l_0),\ \tilde{F}_{\tilde{T}}=\{(|\tilde{t}|,l_{|\tilde{t}|})\},$$
$$l_i\in\Delta,\ i=0,1,\dots,|\tilde{t}|.$$

设$\tilde{q}\in\tilde{Q}_{\tilde{T}}/\{(|\tilde{t}|,l_{|\tilde{t}|})\},\tilde{\sigma}\in\tilde{\Sigma}$,有

$$\tilde{\delta}_{\tilde{T}}(\tilde{q},\tilde{\sigma})=\tilde{\delta}_{\tilde{S}}((\alpha,l_\alpha),\tilde{\sigma})=\begin{cases}((\alpha+1),l_{\alpha+1}),\\ (\tilde{\sigma}=\tilde{\sigma}_{\alpha+1})(l_\alpha\geqslant l_{\alpha+1})((\alpha+1)<|\tilde{t}|);\\ ((\alpha+1),l_\alpha),\\ (\tilde{\sigma}=\tilde{\sigma}_{\alpha+1})(l_\alpha<l_{\alpha+1})((\alpha+1)<|\tilde{t}|);\\ ((\alpha+1),\tilde{F}_{\tilde{S}}^{\gamma}),\ (\tilde{\sigma}=\tilde{\sigma}_{\alpha+1})((\alpha+1)=|\tilde{t}|);\\ ((\max_{i\in\mathrm{match}(\alpha)}i),l_i),\\ (\tilde{\sigma}\neq\tilde{\sigma}_{\alpha+1})(\mathrm{match}(\alpha)\neq\varnothing)((\alpha+1)<|t|);\\ (0,l_0),\ \text{otherwise}.\end{cases}$$

其中

$$\alpha=1,2,\dots,|\tilde{t}|-1;$$
$$\mathrm{match}(\alpha)=\{i:W\bigvee M\},$$
$$W=\{(\tilde{\sigma}_1\dots\tilde{\sigma}_i=\tilde{\sigma}_{\sigma-i+2}\dots\tilde{\sigma}_\alpha\tilde{\sigma})\bigwedge(1<i\leqslant\alpha)\},$$
$$M=\{(i=1)\bigwedge(\tilde{\sigma}_1=\tilde{\sigma})\};$$

$$\gamma=\begin{cases}1+\tilde{E}_{\tilde{K}}^{\tilde{T}}(\tilde{t}),\ \tilde{E}_{\tilde{K}}^{\tilde{T}}(\tilde{t})\geqslant\tilde{E}_{\tilde{K}}(\tilde{u});\\ \tilde{E}_{\tilde{K}}^{\tilde{T}}(\tilde{t}),\ \tilde{E}_{\tilde{K}}^{\tilde{T}}(\tilde{t})<\tilde{E}_{\tilde{K}}(\tilde{u});\end{cases}$$

$\tilde{\delta}_{\tilde{T}}((|\tilde{t}|,\tilde{F}_{\tilde{T}}^{\gamma}),\tilde{\sigma})=(|\tilde{t}|,\tilde{F}_{\tilde{T}}^{\gamma})$.

给定两个FDES: $\tilde{G}_1=(\tilde{Q}_1,\tilde{\Sigma}_1,\tilde{\delta}_1,\tilde{q}_0^1,\tilde{F}_1)$和$\tilde{G}_2=(\tilde{Q}_2,\tilde{\Sigma}_2,\tilde{\delta}_2,\tilde{q}_0^2,\tilde{F}_2)$,定义并行运算

$$\tilde{G}_1\times\tilde{G}_2=(\tilde{Q},\tilde{\Sigma},\tilde{\delta},\tilde{q}_0,\tilde{F}).\tag{19}$$

其中:$\tilde{Q}\subseteq\tilde{Q}_1\times\tilde{Q}_2$;$\tilde{\Sigma}=\tilde{\Sigma}_1\bigcap\tilde{\Sigma}_2$;$\tilde{q}_0=(\tilde{q}_0^1,\tilde{q}_0^2)$;$\tilde{F}=\tilde{F}_1\bigcup\tilde{F}_2$;如果$\tilde{\delta}_1(\tilde{q}_1,\tilde{\sigma})$和$\tilde{\delta}_2(\tilde{q}_2,\tilde{\sigma})$有定义,则$\tilde{\delta}((\tilde{q}_1,\tilde{q}_2),\tilde{\sigma})=((\tilde{\delta}_1(\tilde{q}_1,\tilde{\sigma}))(\tilde{\delta}_2(\tilde{q}_2,\tilde{\sigma})))$.

给定$\tilde{K}\subseteq\tilde{\Sigma}_{\rm pat}^*,\tilde{u}\in\tilde{K},\tilde{\sigma}\in\tilde{u}(\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})])$,则定义S类型模式验证器为一个FDES:

$$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))=(\tilde{X},\tilde{\Sigma}_{\tilde{\sigma}},\tilde{\delta}_{\tilde{\sigma}},\tilde{x}_0,\tilde{F}_{\tilde{S}}).$$

其中:$\tilde{X}$为模糊状态集$\tilde{Q}$的子集,$\tilde{\Sigma}_{\tilde{\sigma}}\subseteq\tilde{\Sigma}$为模糊可观事件集,$\tilde{x}_o$为起始模糊状态,$\tilde{F}_{\tilde{S}}\subset\tilde{X}$为标记可观状态集.

定义7 设$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))=(\tilde{X},\tilde{\Sigma}_{\tilde{\sigma}},\tilde{\delta}_{\tilde{\sigma}},\tilde{x}_0,\tilde{F}_{\tilde{S}})$为$\tilde{G}=(\tilde{Q},\tilde{\Sigma},\tilde{\delta},\tilde{q}_0,\tilde{F})$的S类型模式验证器,并且存在$\tilde{x}=\{\tilde{q}_1^{\tilde{x}},\dots,\tilde{q}_k^{\tilde{x}}\}$,$\tilde{y}=\{\tilde{q}_1^{\tilde{y}},\dots,\tilde{q}_k^{\tilde{y}}\}\in\tilde{X}$,$\tilde{v}\in\tilde{\Sigma}_{\tilde{\sigma}}$,使得$\tilde{y}=\tilde{\delta}_{\tilde{\sigma}}(\tilde{x},\tilde{v})$,即对于$j=1,\dots,m$,存在$i\in\{1,\dots,k\}$,使得$\tilde{q}_j^{\tilde{y}}=\tilde{\delta}(\tilde{q}_j^{\tilde{x}},\tilde{v}\tilde{t}_j)$,其中$\tilde{v}\tilde{t}_j\in\tilde{\Sigma}^*$且$\tilde{t}_j\in(\tilde{\Sigma}/\tilde{\Sigma}_{\tilde{\sigma}})^*$. 如果对于所有$i=1,\dots,k$,都有标记$l_i^{\tilde{x}}\in\tilde{F}_{\tilde{S}}^{\gamma}$,则称此状态为S标记确定;如果存在$i,j\in\{1,\dots,l\}$,有相对应标记$l_i^{\tilde{x}}\in\tilde{F}_{\tilde{S}}^{\gamma}$且$l_j^{\tilde{x}}\in\tilde{X}/\tilde{F}_{\tilde{S}}^{\gamma}$,其中$\gamma>1$,则称此状态为S标记不确定.

定义8 设$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))=(\tilde{X},\tilde{\Sigma}_{\tilde{\sigma}},\tilde{\delta}_{\tilde{\sigma}},\tilde{x}_0,\tilde{F}_{\tilde{S}})$为$\tilde{G}=(\tilde{Q},\tilde{\Sigma},\tilde{\delta},\tilde{q}_0,\tilde{F})$的S类型模式验证器,给定模式故障$\tilde{K}\subseteq\tilde{\Sigma}_{\rm pat}^*,\tilde{u}\in\tilde{K},\tilde{\sigma}\in\tilde{u}(\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})])$. 如果存在$\{\tilde{x}_1,\tilde{x}_2,\dots,\tilde{x}_l\}\subset\tilde{X}$和$\tilde{\sigma}_{o,1},\tilde{\sigma}_{o,2},\dots,\tilde{\sigma}_{o,l}\in\tilde{\Sigma}_{\tilde{\sigma}}^*$,满足:

1) $\tilde{x}_i$为标记不确定的,其中$i=1,\dots,l$.

2) 存在$q_i^k,\tilde{r}_i^l$使得所有$i=1,\dots,m,\ k=1,\dots,M$和$l=1,\dots,N$都满足:

① $\exists\tilde{q}_i^k$被标记为$\tilde{F}_{\tilde{S}}^{\gamma}$,且$\tilde{r}_i^l$被标记为$\Delta/\tilde{F}_{\tilde{S}}^{\gamma}$,其中$\gamma>1$;

② 在$\tilde{G}$中存在两种环,即

$$\begin{aligned}&\tilde{q}_1^1\overset{\tilde{\sigma}_{o,1},\tilde{t}_1^1}{\rightarrow}\tilde{q}_2^1\dots\overset{\tilde{\sigma}_{o,m-1},\tilde{t}_{m-1}^1}{\rightarrow}\tilde{q}_m^1\overset{\tilde{\sigma}_{o,m},\tilde{t}_{m-1}^1}{\rightarrow}\\&\tilde{q}_1^2\dots\overset{\tilde{\sigma}_{o,m-1},\tilde{t}_{m-1}^2}{\rightarrow}\tilde{q}_m^2\dots\tilde{q}_1^M\overset{\tilde{\sigma}_{o,1},\tilde{t}_1^M}{\rightarrow}\\&\tilde{q}_2^M\dots\overset{\tilde{\sigma}_{o,m-1},\tilde{t}_{m-1}^M}{\rightarrow}\tilde{q}_m^M\overset{\tilde{\sigma}_{o,m},\tilde{t}_m^M}{\rightarrow}\tilde{q}_1^1\end{aligned}\tag{20}$$

和

$$\begin{aligned}&\tilde{r}_1^1\overset{\tilde{\sigma}_{o,1},\tilde{u}_1^1}{\rightarrow}\tilde{r}_2^1\dots\overset{\tilde{\sigma}_{o,m-1},\tilde{u}_{m-1}^1}{\rightarrow}\tilde{r}_m^1\overset{\tilde{\sigma}_{o,m},\tilde{u}_{m-1}^1}{\rightarrow}\\&\tilde{r}_1^2\dots\overset{\tilde{\sigma}_{o,m-1},\tilde{u}_{m-1}^2}{\rightarrow}\tilde{r}_m^2\dots\tilde{r}_1^M\overset{\tilde{\sigma}_{o,1},\tilde{u}_1^M}{\rightarrow}\tilde{r}_2^M\\&\dots\overset{\tilde{\sigma}_{o,m-1},\tilde{u}_{m-1}^M}{\rightarrow}\tilde{r}_m^M\overset{\tilde{\sigma}_{o,m},\tilde{u}_m^M}{\rightarrow}\tilde{r}_1^1,\end{aligned}\tag{21}$$

其中对于所有r、k、l,都有$\tilde{E}_M(\tilde{t}_i^k),\tilde{E}_M(\tilde{u}_i^l)<\tilde{E}_o(\tilde{\sigma})$,$\tilde{E}_{\tilde{K}}^{\tilde{S}}(\tilde{\sigma}_{o,1}\tilde{u}_1^1\dots\tilde{\sigma}_{o,i}\tilde{u}_i^l\dots\tilde{\sigma}_{o,m}\tilde{u}_m^N)=\mu<\tilde{E}_{\tilde{K}}(\tilde{u})$,$\tilde{E}_{\tilde{K}}^{\tilde{S}}(\tilde{\sigma}_{o,1}\tilde{t}_1^1\dots\tilde{\sigma}_{o,i}\tilde{t}_i^k\dots\tilde{\sigma}_{o,m}\tilde{t}_m^M)\geqslant\tilde{E}_{\tilde{K}}(\tilde{u})$. 则称此环为程度$\mu$的S标记不确定环.

下面给出S类型故障验证器可诊断性定理,T类故障可类似得到,限于篇幅未详述.

定理1 设$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))=(\tilde{X},\tilde{\Sigma}_{\tilde{\sigma}},\tilde{\delta}_{\tilde{\sigma}},\tilde{x}_0,\tilde{F}_{\tilde{S}})$为$\tilde{G}=(\tilde{Q},\tilde{\Sigma},\tilde{\delta},\tilde{q}_0,\tilde{F})$的S类型模式验证器. 给定模式故障$\tilde{K}\subseteq\tilde{\Sigma}_{\rm pat}^*,\tilde{u}\in\tilde{K},\tilde{\sigma}\in\tilde{u}(\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})])$. $\tilde{G}$为程度是λ的模式可诊断,当且仅当在$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))$中存在最小程度$\mu$的S标记不确定环,其中$\mu=\lambda\tilde{E}_{\tilde{K}}(\tilde{u})$.

证明 必要性. 给定$\tilde{K}\subseteq\tilde{\Sigma}_{\rm pat}^*,\tilde{u}\in\tilde{K},\tilde{\sigma}\in\tilde{u}(\tilde{E}_o(\tilde{\sigma})\in(\tilde{E}_o(\tilde{u}),\tilde{E}_M(\tilde{u})])$. $\tilde{G}$为程度是λ的模式可诊断. 所以在$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))$有$\tilde{\delta}_{\tilde{\sigma}}(\tilde{x}_0,P_{\tilde{\sigma}}(\tilde{s}\tilde{t}))=\tilde{x}$为S标记不确定的,其中$(\tilde{q},|\tilde{u}|\tilde{F}_{\tilde{S}}^{E_{\tilde{K}}^{\tilde{S}}(\tilde{s}\tilde{t})+1})$和$(\tilde{q}',|\tilde{\omega}|N^{E_{\tilde{K}}^{\tilde{S}}(\tilde{\omega})})$为$\tilde{x}$的两个分量,且$\tilde{\omega}\in\Sigma_{\rm pat}^*/\tilde{K}$,记$\tilde{\delta}(\tilde{q}_0,\tilde{s}\tilde{t})=\tilde{q}$,$\tilde{\delta}(\tilde{q}_0,\tilde{\omega})=\tilde{q}'$. $\tilde{G}$的状态为有限的,并且当后续状态数足够大时,$\tilde{x}$的后继状态会形成不确定环$\{\tilde{q}_1,\tilde{q}_2,\dots,\tilde{q}_m\}$和$\{\tilde{q}_1',\tilde{q}_2',\dots,\tilde{q}_m'\}$,其中$(\tilde{q}_i,\tilde{q}_i')=\tilde{x}_i$,$i=1,\dots,m$. 很明显,这两个序列满足定义8的条件,$\{\tilde{x}_1,\tilde{x}_2,\dots,\tilde{x}_m\}$为$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))$中程度为$\mu$的S标记不确定环,其中$\mu=\lambda\tilde{E}_{\tilde{K}}(\tilde{u})$. 假设在$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))$存在另一个$\mu'$的S标记不确定环,则$\tilde{G}$的可诊断程度$\lambda$一定满足

$$\lambda\leqslant\frac{\mu'}{\tilde{E}_{\tilde{K}}(\tilde{u})},$$

即$\mu'\geqslant\lambda\tilde{E}_{\tilde{K}}(\tilde{u})=\mu$. 因此,程度为$\mu$的S标记不确定环$\{\tilde{x}_1,\tilde{x}_2,\dots,\tilde{x}_m\}$为最小程度环.

充分性. 在$\mathrm{Obs}(U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s})))$中存在程度为$\mu$的S标记不确定环,其中$\mu=\lambda\tilde{E}_{\tilde{K}}(\tilde{u})$. 假设$\tilde{G}$的可诊断程度为$x$,根据必要性的证明,验证器中的最小程度环为程度为$\mu'$的S标记不确定环,满足$\mu'=x\tilde{E}_{\tilde{K}}(\tilde{u})$. 对于前者而言,$\mu'\geqslant\mu$;对于后者而言,$\mu\geqslant\mu'$. 也就是说,

$$\lambda\tilde{E}_{\tilde{K}}(\tilde{u})=\mu=\mu'=x\tilde{E}_{\tilde{K}}(\tilde{u}),$$

即$x=\lambda$,所以$\tilde{G}$为程度是λ的模式可诊断. □

为说明验证器,下面以S类型故障为例,T型故障

可类似得到.

例1 考虑如图1所示的FDES, $\tilde{G}=(\tilde{Q},\tilde{\Sigma},\tilde{\delta},\tilde{q}_0,\tilde{F})$, $q_0=[0.9\ \ 0.2\ \ 0]$, 5个事件为

$$\tilde{a}=\begin{bmatrix}0.4&0.9&0.4\\0&0.4&0.4\\0&0&0.4\end{bmatrix},\ \tilde{b}=\begin{bmatrix}0.9&0&0\\0.9&0.4&0\\0.4&0.4&0.4\end{bmatrix},$$

$$\tilde{c}=\begin{bmatrix}0.9&0.9&0.4\\0&0.4&0.4\\0&0&0.4\end{bmatrix},\ \tilde{d}=\begin{bmatrix}0.5&0&0\\0.1&0.1&0\\0.1&0.1&0.1\end{bmatrix},$$

$$\tilde{e}=\begin{bmatrix}0.5&0.9&0.6\\0&0.6&0.6\\0&0&0.6\end{bmatrix}.$$

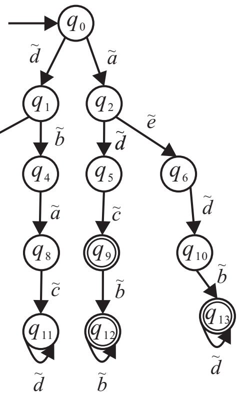

图1 $\tilde{G}$

假设各事件可观程度分别为

$$\tilde{E}_o(\tilde{a})=0.3, \tilde{E}_o(\tilde{b})=0.7, \tilde{E}_o(\tilde{c})=0.2,$$
$$\tilde{E}_o(\tilde{d})=0.6, \tilde{E}_o(\tilde{e})=0.1.$$

对于每个事件在模式故障中发生的可能性假设为

$$\tilde{E}_{\tilde{K}}(\tilde{a})=0.3, \tilde{E}_{\tilde{K}}(\tilde{b})=0.4, \tilde{E}_{\tilde{K}}(\tilde{c})=0.2,$$
$$\tilde{E}_{\tilde{K}}(\tilde{d})=0.3, \tilde{E}_{\tilde{K}}(\tilde{e})=0.1.$$

假设$\tilde{K}=\{\tilde{a}\tilde{b}\}$,用定义5的方法判断$\tilde{G}$是否为模式可诊断.

由图1可得, $\tilde{G}$的生成语言为

$$\tilde{L}=\overline{\tilde{d}(\tilde{e}\tilde{c}\tilde{b}^*+\tilde{b}\tilde{a}\tilde{c}\tilde{d}^*)+\tilde{a}(\tilde{d}\tilde{c}\tilde{b}\tilde{b}^*+\tilde{e}\tilde{d}\tilde{b}\tilde{d}^*)}.$$

由于系统存在与模式故障$\tilde{K}=\{\tilde{a}\tilde{b}\}$发生相同故障效果的模糊事件序列串$\{\tilde{b}\tilde{d}\}\in\tilde{\Sigma}^*_{\mathrm{pat}}$,且$\tilde{b}\tilde{d}$存在不同的发生模式故障的可能性. 因此,系统将会发生非完全模式可诊断的现象. 在$\tilde{L}$中含有$\tilde{K}$模式故障子序列的事件串集为

$$\tilde{S}=\{\tilde{d}\tilde{e}\tilde{c}\tilde{b}^l,\tilde{a}\tilde{d}\tilde{c}\tilde{b}\tilde{b}^m,\tilde{a}\tilde{e}\tilde{d}\tilde{b}\tilde{d}^r|l,m,r\geqslant 0\},$$

从而可得$\Psi_{\tilde{S}}(\tilde{K})=\{\tilde{a}\tilde{d}\tilde{c}\tilde{c}\tilde{b}^m,\tilde{a}\tilde{e}\tilde{d}\tilde{b}|m\geqslant 0\}$.

取$\tilde{s}_1=\{\tilde{a}\tilde{d}\tilde{c}\tilde{c}\tilde{b}^m,\tilde{a}\tilde{e}\tilde{d}\tilde{b}|m\geqslant 0\}$, $\tilde{t}_1\in\tilde{L}/\tilde{s}_1$且$|\tilde{t}_1|\geqslant 0$,进而得到$P_{\tilde{\sigma}}^{-1}P_{\tilde{\sigma}}(\tilde{s}_1\tilde{t}_1)\bigcap\tilde{L}=\{\tilde{d}\tilde{e}\tilde{c}\tilde{b}^l,\tilde{a}\tilde{d}\tilde{c}\tilde{b}\tilde{b}^m,\tilde{a}\tilde{e}\tilde{d}\tilde{b}\tilde{d}^r|l,m,r\geqslant 0\}$,所以可得

$$\mathrm{FD}^{\tilde{S}}_{\tilde{K}}(\tilde{s}_1\tilde{t}_1)=\max_{\tilde{u}\in\tilde{K}}\left\{\frac{D}{\tilde{E}_{\tilde{K}}(\tilde{u})}\right\}=0.67,$$
$$D=\min\{\tilde{E}_{\tilde{K}}(\tilde{u}),\tilde{E}^{\tilde{S}}_{\tilde{K}}(\tilde{\omega})|\tilde{\omega}\in P_{\tilde{\sigma}}^{-1}P_{\tilde{\sigma}}(\tilde{s}\tilde{t})\subseteq\tilde{S}\},$$

即系统$\tilde{G}$可诊断程度为0.67.

下面用定理的方法(即定理1)验证这个结论. 首先,构造并行FDES: $\Theta=U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s}))$和$\mathrm{Obs}(\Theta)$,如图2和图3所示. 图3中, $\tilde{G}$存在最小程度$\mu=0.2$的S标记不确定环,因此由定理1可得, $\tilde{G}$为程度是$\lambda=0.67$的模式可诊断.

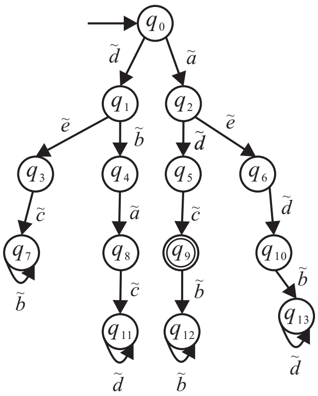

图2 $\Theta=U_{\tilde{s}\in\tilde{K}}(\tilde{G}\times\tilde{H}_{\tilde{S}}(\tilde{\Sigma},\tilde{s}))$

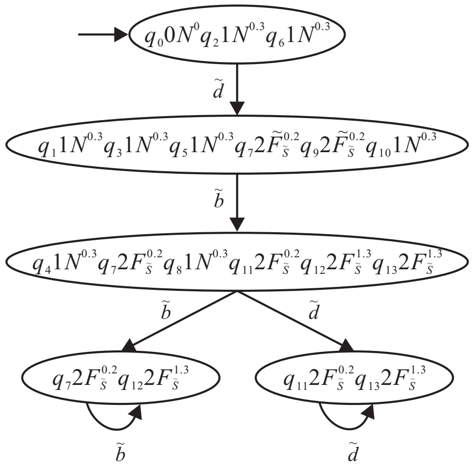

图3 $\mathrm{Obs}(\Theta)$

4 结 论

本文针对模糊系统提出了一种基于验证器的模糊离散事件系统模式故障诊断方法,在此研究的基础上,还可以进一步考虑模糊离散事件系统模式故障诊断的安全性问题以及赋时离散事件系统的模式故障诊断等问题,这些问题将在后续的研究中继续进行探讨.

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