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부분관측하에서 직렬생산시스템의 멀티에이전트 내고장성 관리제어에 관한 연구

(Multiagent Fault-Tolerant Supervisory Control of Serial Production Systems Under Partial Observation)

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요 약

이 논문에서는 부분관측하에서 직렬생산시스템에 대한 멀티에이전트 내고장성 관리제어기법을 제안한다. 이를 위해 기존의 이산사건시스템에 대한 내고장성 관리제어기법에 멀티에이전트 제어기법의 개념을 도입한다. 특히, 직렬연결된 프로세서 사이의 상호 내고장성 개념을 정립하며 제어결과의 상이정보를 이용한 관측불능 고장 식별에 관해 다룬다. 그리고 정립된 개념을 바탕으로 에이전트 관리제어기의 설계기법을 정형화한다. 또한 제안하는 제어기법의 효용성을 검증하기 위해 폴리프로필렌의 예비중합공정과 중합공정에 있어서의 고장파급제어에 대한 사례연구를 살펴본다.

Abstract

In this paper, a multiagent fault-tolerant supervisory control methodology is proposed for serial production systems under partial observation. To this end, the idea of multiagent control is incorporated with the fault-tolerant supervisory control of discrete event systems. Especially, the concept of mutual fault-tolerance between cascaded processes is established and the unobservable fault identification utilizing the difference information of the controlled results is investigated. Then the synthesis of agent supervisors is formulated based on the proposed concept. A case study of the fault-propagation control of polypropylene prepolymerization and polymerization processes is provided to illustrate the proposed control policy.

I. Introduction

Discrete event systems (DESs)[1],[3] have attracted much attention in the systems modeling area and within the control-law synthesis field. A DES is a dynamic system whose evolution in time is governed by the abrupt occurrence of physical events, at possibly irregular intervals. Many large-scale dynamic systems, especially man-made systems, show the DES characteristics at least at some level of abstraction. Some examples include manufacturing systems, computer systems, communication networks, and traffic management systems.

Most of the industrial systems are composed of serial production systems. In such serial

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production systems, maintaining the continuous process operation is most important to prevent the depreciation in productivity and to protect the facilities from the abnormal situations. Especially, in chemical industry, an instantaneous interruption of the process due to a momentary trouble could be led to tremendous losses and severe damages of the system because of the long delay time accompanying complicated restart-up procedures and the obstruction effects of the by-products such as the plugging of the transfer lines. Therefore, to continue the overall process in spite of the momentary trouble due to some disturbances, identifying the current status and preventing any fault-propagation between unit processes by certain supervisory control actions are most preferable.

Within the DES framework, the diagnostic issues over various fields have been studied up to the present: the fault detection and isolation problems are dealt with in[4],[7] and the failure analysis with the corresponding system controller design is addressed in [8]. Especially in [8], the abnormal status in the behavior of the DES was quantitatively analyzed upon a discrete event model (DEM)[9] and the synthesis of fault-tolerant supervisor was introduced based on the failure analysis. However, this way of approach in [8] becomes intractable for large complex systems such as serial production systems which are common in most of the production industries, due to the state explosion in the DEMs. Moreover, the synthesis of decentralized supervisor[10][13] (which is the most promising way to reduce the complexity) still needs much complicated steps in the design stage to guarantee the same optimal behavior as the centralized supervisor and can not deal with the problem of fault-propagation between unit processes (i.e., local plants). Furthermore, the problem also lies in the fact that the abnormal events of faults or failures might not be observable at the external worlds.

To resolve these problems, it is required to consider a new concept of fault-tolerant supervisory control which independently supervises each unit process and shares the least amount of information just needed to prevent the unobservable fault-propagation between unit processes. To this end, we make use of the difference information of the controlled results at each unit process in identifying the occurred fault events and reconfiguring the posterior agent supervisor. In this way, the unobservable fault events caused by some momentary troubles could be compensated and prevented from propagation into the posterior processes by a certain external control action, resulting in improvement of productivity and protection of facilities, accordingly. Therefore, in this paper, we propose a multiagent fault-tolerant supervisory control methodology for serial production systems under partial observation by incorporating the concept of multiagent control [14],[16] with the fault-tolerant supervisory control scheme.

The paper is organized as follows. In the remainder of this section we give some notation. Section 2 briefly reviews an automata-theoretic DEM with the supervisory control framework. In Section 3, we present the method of inferring the occurrence of unobservable abnormal events through the difference information of the controlled results. In Section 4, the reconfiguration of the posterior agent supervisor for multiagent fault-tolerant supervisory control based on the identification of the compensable events are described. In Section 5, the case study of the control of polypropylene prepolymerization and polymerization processes is provided. Finally, the conclusions are formulated in Section 6.

Notation	
$\sum_{G(q)}$	active event set of G at the state q [2]
$D(e, y)[D(s, y)]$	starting state of the event e[string s] leading to y (domain of e [s] leading to y)
$R(e, x)[R(s, x)]$	ending state of the event e [string s] from x (range of e [s] from x) — $R(e)[R(s)]$ is to be used instead of $R(e, q_0)[R(s, q_0)]$ where q_0 is the initial state of the deterministic automaton
$\overline{K}$	prefix closure of $K(=\{p\in\Sigma^*(\exists t\in\Sigma^*)pt\in K\})$
$R(\bar{s}, x)$	$\{q\in Q \mid q=R(s', x)$ for each $s'\in\bar{s}$ with $R(\varepsilon, x)=x\}$ where Q is the state set and $\bar{s}$ is the prefix closure of s -$R(\bar{s})$ is to be used instead of $R(\bar{s}, q_0)$
$R(L)$	range of the language L ($\{q\in Q \mid q=R(l)$ for each $l\in L\}$ where l is a kind of string s, especially an element of the language L) — in this case, always $R(L)=R(L, q_0)$
aug-event	event augmented with its originating state ((σ, q) with $R(\sigma, q)=\delta(\sigma, q)$ where $\delta:\sum\times Q\mapsto Q$ is the transition function [1])
$Evn(s)$	set of events which constitute the string s
$\vert s\vert$	number of events comprising the string s (length of the string s)
L_1+L_2	$\{l\in\Sigma^* \mid l\in L_1$ or $l\in L_2\} = L_1\cup L_2$
$G_1\cup G_2$	recognizer automaton [1] for $L(G_1)+L(G_2)$
$C_G(K)$	controllable sublanguage [1], [2] of $K\subseteq L(G)$

II. Background Review

This work is set in the supervisory control framework for DESs developed by Ramadge and Wonham [1-2]. A brief review of the key concepts is given in the following:

The plant to be controlled is modeled by an automaton $G=(\Sigma, Q, \delta, q_0, Q_m)$ where Σ is an alphabet of event labels, Q is a set of states, $q_0\in Q$ is the initial state, $Q_m\in Q$ is the set of *marker states*, and $\delta:\Sigma\times Q\mapsto Q$, the transition function, is a partial function defined at each state in Q for a subset of Σ. For the case where Q is finite, G can be represented by a finite state machine whose nodes are states and whose edges are transitions defined by δ. On the transition diagram, the initial state is identified by an arrow entering it and marker states by an arrow leaving them. The set Σ is the set of all edge labels on the diagram.

Let Σ^* denote the set of all finite strings over Σ including the null string ε. Then δ can be extended to Σ^* by defining $\delta(\varepsilon, q):=q$ and $(\forall\sigma\in\Sigma, s\in\Sigma^*):\delta(s\sigma, q):=\delta(\sigma, \delta(s, q))$. Then G is characterized by two subsets of Σ^* called the *closed behavior* of G, written $L(G)$, and the *marker behavior* of G, written $L_m(G)$. The language $L(G)$ is defined as

$$[L(G):=\{s \mid s\in\Sigma^* \text{ and } \delta(s, q_0) \text{ is defined}\}$$

and is interpreted to mean the set of all possible event sequences which the plant may generate. The language $L_m(G)$ is defined as

$$L_m(G):=\{s \mid s\in\Sigma^* \text{ and } \delta(s, q_0)\in Q_m\}$$

and is intended to distinguish some subset of possible plant behavior as representing completed tasks.

To impose supervision on the plant, we identify some of its events as *controllable* and some as *uncontrollable*, thereby partitioning Σ into the disjoint sets Σ_c, the set of controllable events, and Σ_{uc}, the set of uncontrollable events. Controllable events are those which an external agent may enable or disable while uncontrollable events are those which cannot be prevented from occurring and are therefore considered to be permanently enabled. A supervisor is then an agent which observes a sequence of events as it generated by G and enables or disables any of the controllable events at any point in time throughout its observation. By performing such a manipulation of controllable events, the supervisor ensures that only a subset of $L(G)$, called a *sublanguage*, is permitted to be generated. Formally, a *supervisor* S is a pair (S, ϕ) where S is an automaton which recognizes a language over the same event set as the plant G and ϕ, called a *feedback map*, is a map from the event set and states of S to the set {1(enable), 0(disable)}. If X denotes the set of states of S, then $\phi : \Sigma \times X \mapsto 1, 0$ satisfies

$$\phi(\sigma, x) = 1 \text{ if } \sigma \in \Sigma_{uc},\ x \in X$$

and

$$\phi(\sigma, x) \in \{1, 0\} \text{ if } \sigma \in \Sigma_c, x \in X.$$

The automaton S tracks and controls the behavior of G. It changes state according to the events generated by G and in turn, at each state x of S, the control rule $\phi(\sigma, x)$ dictates whether σ is to be enabled or disabled at the corresponding state of G.

The behavior of the closed-loop system, i.e., the sequences of events generated while the plant is under the control of $S = (S, \phi)$, is represented by an automaton S/G whose closed behavior, denoted by $L(S/G)$, permits a string to be generated if the string is in both G and S and if each event in the string is enabled by ϕ. Define $L_c(S/G)$ as those (marked) strings of the uncontrolled process language that survive in the presence of supervision, i.e.,

$$L_c(S/G) := L(S/G) \cap L_m(G).$$

The closed-loop system's marked behavior is denoted by $L_m(S/G)$ and consists of those strings in $L(S/G)$ that are marked by both G and S.

Ⅲ. Fault Identification and Multiagent Supervisory Control for Mutual Fault-Tolerance

In this section, we introduce an unobservable fault identification scheme and a concept of multiagent fault-tolerant supervisory control of serial production systems based on the identification scheme.

Consider the serial production systems composed of unit process $G_i[k]$, $i \in [1, I]$ and $k \in [0, \infty]$ — ith unit process executing kth operation — cconnected in tandem. The supervisor $S^{p}_{A_i}$ of each unit process $G_i[k]$ is to be called a partial *agent supervisor* and the corresponding integrated action of control is to be called *multiagent supervisory control*. In other words, the multiagent supervisory control is a cooperative integration of agent supervisors with high autonomy and the least common information for the overall control objectives. This kind of multiagent supervisory control concept can be distinguished from the decentralized supervisory control methodology [10]-[13] in that it allows independent synthesis of each agent supervisor resulting in reduced complexity at design stage and it also provides a framework in which the problem of fault-propagation between unit processes can be dealt with. The configuration of multiagent supervisory control for serial production systems is illustrated in Fig. 1, where a partial agent supervisor $S^p_{A_i}$ controls $G_i[k]$ through the feedback map ϕ_i and transfers the coded information $f(\cdot)$ of an actually occurred sequence $l_{ao}(S^{A_{ip}}/G_i[k])$ after supervision through the projection map $P:\Sigma_i^* \mapsto \Sigma_{i,o}^*$ to $S^p_{A_{i+1}}$ where Σ_i is the set of all possible events for $G_i[k]$ and $\Sigma_{i,o}$ is the set of observable events of Σ_i and then gets the feedback information $g_{i+1}(\cdot)$ from $S^p_{A_{i+1}}$. Based on $g_{i+1}(\cdot)$, $S^p_{A_i}$ determines whether it keeps controlling or stops the current process and starts diagnosis.

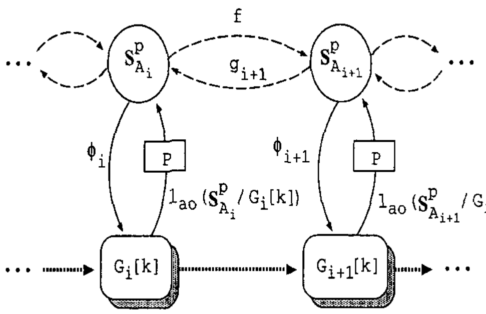

그림 1. 부분관측하에서 직렬생산시스템의 멀티에이전트 관리제어

Fig. 1. Multiagent supervisory control of serial production systems under partial observation.

Note that $G_i[k] = G_i^n[k] \cup G_i^f[k]$ where $G_i^n[k]$ represents the normal mode consisting of observable event sequences and $G_i^f[k]$ the fault mode including certain unobservable abnormal events, which implies some possible abnormal status in the operation. $S^p_{A_i}$ can be designed based on the legal language K_i such that $K_i = L_c(S^p_{A_i}/G_i^n[k])$[1] as usual if K_i is achievable — i.e., controllable and observable. Since K_i is assumed to be observable, K_i becomes achievable if we choose $K_i \subseteq \mathbf{C}_{G_i^n[k]}(L(G_i^n[k]))$ [2]. However, in the closed loop operation, $L(S^p_{A_i}/G_i[k]) = L(S^p_{A_i}/G_i^n[k]) + L(S^p_{A_i}/G_i^f[k]) = K_i + K_f$ where K_f shows the abnormal operation due to some malfunctions. Such abnormal status of DESs [1], [3] was further classified into a 'fault' representing a rather tolerable malfunction and a 'failure' implying a complete breakdown of the overall system operation in[8]. Based on the failure analysis, it was shown that in the case of occurrence of faults the control objectives still can be satisfied by reconfiguring the operation event sequence according to the supervisory control actions, which results in the fault-tolerant operation. This idea was developed upon a DEM of a single process. In the line of extension of these concepts to the multiagent supervisory control of serial production systems, we can consider the failure analysis of multiprocesses as follows : For each unit process, the abnormal status can be analyzed as a fault and a failure according to the previous notion. The failure, in this case, can be further classified into a failure that propagate to the posterior process but can be compensated by the agent supervisor, and a failure that propagate and not compensable by any measure or do not propagate and leads to a breakdown of the current process. The former one can be dealt with as a fault in the framework of multiagent supervisory control since it is possible to continue the overall process without interruption through a pertinent supervisory control action of the corresponding agent supervisor. In view of failure analysis and fault-tolerant supervisory control, this property is to be called *mutual fault-tolerance.*

Definition 1 : *The multiagent supervisory control system over* $S^p_{A_i}$ *and* $S^p_{A_{i+1}}$ *is mutually fault-tolerant between* $G_i[k]$ *and* $G^n_{i+1}[k]$ *if any fault propagation from* $G_i[k]$ *into* $G^n_{i+1}[k]$ *can be eliminated by the subsequent agent supervisor* $S^p_{A_{i+1}}$ *for all* $k \in [0, \infty]$. Furthermore, the multiagent supervisory control system over $G_i[k], i \in [1, I]$ is called a *mutually fault-tolerant system* if it is mutually fault-tolerant for all $i \in [1, I]$. Therefore, the multiagent fault-tolerant supervisory control can be considered as a kind of multiagent supervisory control assuring the mutually fault-tolerant system in the closed loop operation.

The problem lies in the fact that the abnormal events are often not observable. Let the set of events of $G_i[k]$, Σ_i be partitioned as $\Sigma_i = \Sigma_{i,n} \dot{\cup} \Sigma_{i,an} = \Sigma_{i,o} \dot{\cup} \Sigma_{i,uo}$ where $\Sigma_{i,n}$ is the set of normal events of Σ_i, $\Sigma_{i,an}$ is the set of abnormal events of Σ_i, $\Sigma_{i,o}$ is the set of observable events of Σ_i, and $\Sigma_{i,uo}$ is the set of unobservable events of Σ_i. Assume that we know all the possible occurrence of abnormal events and we can compare the status of the controlled plant in kth operation with that of $(k-1)$th operation after the transition from the possible occurrence states. This is feasible just by setting up some comparators at each possible occurrence point rather than installing the expensive sensors to obtain the direct information about the internal status, which also might be impossible. Consider $l[k] \in \bar{l}_{ao}(S^p_{A_i}/G_i[k])$ and $\sigma^k \in \Sigma_{G_i[k]}(R(l[k])) = \{\sigma_{an}, \sigma_n\}$ with $\sigma_{an} \in \Sigma_{i,an} \cap \Sigma_{i,uo}, \sigma_n \in \Sigma_{i,n}$ in Fig.2. Then we can identify the occurrence of σ_{an} for σ^k after $l[k]$ from the following unobservable fault identification (UFI) algorithm:

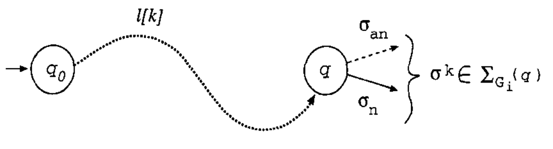

그림 2. 관측불가능한 이상사건의 발생상황
Fig. 2. Occurrence of the unobservable abnormal event.

<u>**UFI Algorithm**</u>

Step 1 : *Let* $\lambda(\sigma^0) = \nu(\sigma^0) = 0$ *where* $\lambda: \Sigma \mapsto 0,1$ *and* $\nu: \Sigma \mapsto \{0,1\}$.

Step 2 : *For* $k \in [1, \infty]$,

1) *compute* $\lambda(\sigma^k) = unit(|R(l[k]\sigma^k) - R(l[k-1]\sigma^{k-1})|)$

where $unit(x) = 1$ if $x > 0$ and 0 *otherwise*, and

2) *compute* $\nu(\sigma^k) = \lambda(\sigma^k)[1 - \nu(\sigma^{k-1})] + \nu(\sigma^{k-1})[1 - \lambda(\sigma^k)]$

Step 3 : *If* $\nu(\sigma^k) = 1$ *then* $\sigma^k \in \Sigma_{i,an}$.

Note that the value of $\lambda(\sigma^k)$ actually corresponds to the comparator output indicating the difference information of the controlled results. In UFI Algorithm, if $\sigma^{k-1} \in \Sigma_{i,n}$ and $\sigma^k \in \Sigma_{i,an}$ then $\nu(\sigma^{k-1}) = \lambda(\sigma^{k-1}) = 0$ and $\nu(\sigma^k) = \lambda(\sigma^k) = 1$, and vice versa. If $\sigma^{k-1} \in \Sigma_{i,an}$ and $\sigma^k \in \Sigma_{i,an}$ then $\nu(\sigma^{k-1}) = 1$, $\lambda(\sigma^{k-1}) = 1$ or 0, both of which result in $\nu(\sigma^k) = 1$, $\lambda(\sigma^k) = 0$. If $\sigma^{k-1} \in \Sigma_{i,an}$ and $\sigma^k \in \Sigma_{i,n}$ then $\lambda(\sigma^{k-1}) = 0$, $\nu(\sigma^{k-1}) = 1$ and $\lambda(\sigma^k) = 1$, $\nu(\sigma^k) = 0$. If $\sigma^{k-1} \in \Sigma_{i,n}$ and $\sigma^k \in \Sigma_{i,n}$ then $\lambda(\sigma^{k-1}) = 1$ or 0, $\nu(\sigma^{k-1}) = 1$, and $\lambda(\sigma^k) = \nu(\sigma^k) = 0$. Therefore, we can identify the occurrence of any unobservable abnormal event according to UFI Algorithm. Once we identify such an occurrence of the abnormal event, we can determine whether it is compensable by certain complementary measure and can reconfigure the posterior agent supervisor accordingly such that the overall process is continued without interruption.

Assume that the total set of events of $G_i[k]$, Σ_i can be partitioned as $\Sigma_i = \Sigma_{i,c} \dot{\cup} \Sigma_{i,uc} = \Sigma_{i,n} \dot{\cup} \Sigma_{i,an} = \Sigma_{i,n} \dot{\cup} (\Sigma_{i,cb} \dot{\cup} \Sigma_{i,ucb})$ where $\Sigma_{i,c}$ is the set of controllable events of Σ_i, $\Sigma_{i,uc}$ is the set of uncontrollable events of Σ_i, $\Sigma_{i,cb}$ is the set of compensable events of $\Sigma_{i,an}$, and $\Sigma_{i,ucb}$ is the set of uncompensable events of $\Sigma_{i,an}$. Let $S_{FT_{i,i+1}}$ be a fault-tolerant supervisor of $G_{i,i+1}[k] = G_i[k] \| G^n_{i+1}[k]$ where $\|$ denotes the composition of two DEMs[9], and $L_{FT_{i,i+1}}[k] = L(S_{FT_{i,i+1}}/G_{i,i+1}[k])$. In the foregoing, $\sigma_{i,cb} \in \Sigma_{i,cb}$ implies that there exists a complementary measure $\sigma_{i+1,cm} \in \Sigma_{i+1,cm} \subset \Sigma_{i+1,c}$ such that $R(l_i^1 \sigma_{i,cb} l_i^2 l_{i+1}^1 \sigma_{i+1,cm} l_{i+1}^2) = R(l_i^{1'} l_i^{2'} l_{i+1}^{1'} l_{i+1}^{2'}) \in R(L_{FT_{i,i+1}}[k])$ for some $l_i^{1'}, l_i^{2'} \in \Sigma_{i,n}^*$ and $l_{i+1}^{1'}, l_{i+1}^{2'} \in \Sigma_{i+1,n}^*$ where $\Sigma_{i+1,cm}$ is the set of complementary measures in Σ_{i+1}, $l_i^1 \sigma_{i,cb} l_i^2 \in L(G_i[k])$, $l_{i+1}^1 \sigma_{i+1,cm} l_{i+1}^2 \in \mathbf{C}_{G_{i+1}^n}[k](L(G_{i+1}^n[k]))$, $l_i^{1'} l_i^{2'} \in L(G_i[k])$, and $l_{i+1}^{1'} l_{i+1}^{2'} \in L(G_{i+1}^n[k])$. Then we can consider the following *domain of fault-tolerance*:

Definition 2 : *The domain of fault-tolerance of $G_i[k], R_{FT_i}[k]$ is the set of states of $G_{i-1}[k]$, from which any postlanguages could be supplemented to meet the mutual fault-tolerance between $G_{i-1}[k]$ and $G_i^n[k]$ by the subsequent agent supervisor $S_{A_i}^p$.*

Along with the previous definitions about $\Sigma_{i,ucb}$, it becomes $R_{FT_{i+1}}[k] = \{ q \in Q_i \mid q \in R(L(G_i[k]) - L_{ucb}(G_i[k]))\}$ where $L_{ucb}(G_i[k]) = \{ l \in L(G_i[k]) \mid Evn(l) \cap \Sigma_{i,ucb} \neq \phi\}$. The following Proposition 1 provides the existence condition of $S_{A_{i+1}}^p$ satisfying the mutual fault-tolerance between $G_i[k]$ and $G_{i+1}^n[k]$.

Proposition 1 : *There exists an achievable K_{i+1} such that $l_{ao}(S_{A_i}^p/G_i[k])K_{i+1} \in L_{FT_{i,i+1}}[k]$ if and only if $R(l_{ao}(S_{A_i}^p/G_i[k])) \in R_{FT_{i+1}}[k]$ where $l_{ao}(S_{A_i}^p/G_i[k])$ is the actually occurred sequence over $L(S_{A_i}^p/G_i[k])$.*

Proof: (If) Assume $Evn(l_{ao}(S_{A_i}^p/G_i[k])) \cap \Sigma_{i,an} \neq \phi$ then $Evn(l_{ao}(S_{A_i}^p/G_i[k])) \cap \Sigma_{i,an} \subset \Sigma_{i,cb}$ from $R(l_{ao}(S_{A_i}^p/G_i[k])) \in R_{FT_{i+1}}[k]$ and $R(L(G_i[k]) - L_{ucb}(G_i[k])) \cap R(L_{ucb}(G_i[k])) = \phi$. If $\sigma_{i,cb} \in Evn(l_{ao}(S_{A_i}^p/G_i[k])) \cap \Sigma_{i,an}$ occurs, then we can choose $K_{i+1} = l_{i+1}^1 \sigma_{i+1,cm} l_{i+1}^2 \in \mathbf{C}_{G_{i+1}^n[k]}(L(G_{i+1}^n[k]))$ where $\sigma_{i+1,cm} \in \Sigma_{i+1,cm}$ and $l_{i+1}^1, l_{i+1}^2 \in \Sigma_{i+1,n}^*$ such that $R(l_{ao}(S_{A_i}^p/G_i[k])K_{i+1}) = R(l_i^1 \sigma_{i,cb} l_i^2 l_{i+1}^1 \sigma_{i+1,cm} l_{i+1}^2) = R(l_i^{1'} l_i^{2'} l_{i+1}^{1'} l_{i+1}^{2'}) \in R(L_{FT_{i,i+1}}[k])$ in which $l_i^1, l_i^2 \in \Sigma_{i,n}^*, l_i^{1'}, l_i^{2'} \in \Sigma_{i,n}^*$ and $l_{i+1}^{1'} l_{i+1}^{2'} \in \Sigma_{i+1,n}^*$. So $l_{ao}(S_{A_i}^p/G_i[k])K_{i+1} \in L_{FT_{i,i+1}}[k]$. (Only if) On the other hand, if $R(l_{ao}(S_{A_i}^p/G_i[k])) \notin R_{FT_{i+1}}[k]$ then $\exists \sigma_{i,ucb} \in Evn(l_{ao}(S_{A_i}^p/G_i[k]))$ and $l_{ao}(S_{A_i}^p/G_i[k]) \notin \overline{L}_{FT_{i,i+1}}[k]$ resulting in $l_{ao}(S_{A_i}^p/G_i[k])K_{i+1} \notin L_{FT_{i,i+1}}[k]$ for any $K_{i+1} \in \mathbf{C}_{G_{i+1}^n[k]}(L(G_{i+1}^n[k]))$. Therefore, $\exists K_{i+1} \in \mathbf{C}_{G_{i+1}^n[k]}(L(G_{i+1}^n[k]))$ such that $l_{ao}(S_{A_i}^p/G_i[k])K_{i+1} \in L_{FT_{i,i+1}}[k]$ implies $R(l_{ao}(S_{A_i}^p/G_i[k])) \in R_{FT_{i+1}}[k]$.

Ⅳ. Synthesis of Agent Supervisors for Fault-Tolerance

In this section, we consider the reconfiguration of agent supervisors for multiagent fault-tolerant supervisory control based on the existence condition of K_{i+1} in Proposition 1. Let, for each $\sigma_{i,cb} \in \Sigma_{i,cb}$, $\mu : \Sigma_{i+1} \mapsto \Re$ *and* $\mu^c : \Sigma_i \mapsto \Re$ be defined such that $\mu(\sigma_{i+1,cm}) = \mu^c(\sigma_{i,cb})$ for the corresponding $\sigma_{i+1,cm} \in \Sigma_{i+1,cm}$ where $\Re$ means the set of real numbers and $\mu^c(\cdot)$ implies the mathematical complement of $\mu(\cdot)$ such as 2's complement in case of a binary number. These could be listed in the complementary measures table (CMT) at the outset. Note that all the abnormal events including the compensable events are assumed to be identified by utilizing the comparator outputs as it follows from UFI Algorithm. Let $f^e : \Sigma_i \times Q_i \mapsto \Re$ be defined for each $\sigma \in Evn(l_{ao}(S_{A_i}^p/G_i[k]))$ and $f : \Sigma_i \times Q_i \times N \mapsto \Re$ be a function composed of a sequence of f^e, for a certain coded information of $l_{ao}(S_{A_i}^p/G_i[k])$. Furthermore, let $\eta : \Re \mapsto \Re$ be a function representing the orderly information of $f^e(\cdot)$ for the successive events comprising $l_{ao}(S_{A_i}^p/G_i[k])$. Based on these, we choose a function $h : \Sigma_i^* \times \Re \mapsto \Sigma_{i+1}^*$ such that $K_{i+1} = h(L(G_{i+1}^n[k]), f(l_{ao}(S_{A_i}^p/G_i[k]))) = \{k_{i+1} \in L(G_{i+1}^n[k]) \mid$

$f(k_{i+1})=f^c(l_{ao}(S^p_{A_i}/G_i[k]))\}$ where $f(k_{i+1})=f^c(l_{ao}(S^p_{A_i}/G_i[k]))$, for $f^c:\Sigma_i^*\mapsto\Re$, implies $\mu(e_t^{i+1})=\mu^c(e_r^i)$, if $f^e(e_r^i,q)\neq\eta(f^e(e_{r-1}^i,q))$ with $e_r^i\in\Sigma_{i,an}$, for some $e_t^{i+1}\in Evn(k_{i+1})$ in which $e_r^i, e_{r-1}^i\in Evn(l_{ao}(S^p_{A_i}/G_i[k]))$, $r\in[0,\bar{r}]$ with $\bar{r}=|l_{ao}(S^p_{A_i}/G_i[k])|$, and $t\in[0,\bar{t}]$ with $\bar{t}=|k_{i+1}|$, and $f^e(e_t^{i+1},q)=\eta(f^e(e_{t-1}^{i+1},q))$, otherwise.

In addition to the supervisory control actions, $S^p_{A_{i+1}}$ also provides the feedback information $g_{i+1}(\cdot)$ to $S^p_{A_i}$ such that it can determine whether it keeps controlling $G_i[k]$ or stops and starts diagnosis. The feedback information $g_{i+1}:\Sigma_i^*\mapsto\{0,1\}$ is defined as $g_{i+1}(l_{ao}(S^p_{A_i}/G_i[k]))=1$ if $R(l_{ao}(S^p_{A_i}/G_i[k]))\in R_{FT_{i,i+1}}[k]$ and 0 otherwise. In this case, $g_{i+1}(\cdot)=1$ is interpreted as 'keep controlling' and 0 'stop and diagnose' by $S^p_{A_i}$.

Based on Proposition 1 and the corresponding K_{i+1}, we can reconfigure $S^p_{A_{i+1}}$ for $G^n_{i+1}[k]$ into (S_{i+1},ϕ_{i+1}) such that it assures the mutual fault-tolerance between $G_i[k]$ and $G^n_{i+1}[k]$ as follows, where S_{i+1} is a recognizer automaton [1] for K_{i+1} and ϕ_{i+1} is the feedback map:

Synthesis Procedures for Reconfiguration

1. S_{i+1}: Build up $S_{i+1}=(X_{i+1},\ \Sigma_{i+1},\ \xi_{i+1},\ x_{i+1,0},\ X_{i+1,m})$ such that it recognizes K_{i+1}.

2. ϕ_{i+1}: Build up $\phi_{i+1}:X_{i+1}\times\Sigma_{i+1}\times\{0,1\}\mapsto\{0,1\}^\Sigma$ as

$$\phi_{i+1}(x_{i+1},\sigma,g_{i+2}(s))=\begin{cases}1, & \text{if } s\sigma\in\overline{K}_{i+1} \text{ and } g_{i+2}(s)=1\\ 0, & \text{otherwise,}\end{cases}$$

in which $s\in\overline{L}(S^p_{A_{i+1}}/G^n_{i+1}[k])$, $R(s)=x_{i+1}$, and $\sigma\in\Sigma_{i+1}$.

Suppose $\sigma^r_{i,an}\in\Sigma_{i,an}$ occurred after $\sigma_i^{r-1}\in\Sigma_i$ such that $L_c(S^p_{A_i}/G_i[k])\neq K_i$ (i.e., $f^e(\sigma^r_{i,an}\ q)\neq\eta(f^e(\sigma_i^{r-1},q))$) because of $G^f_i[k]$ where $K_i=L_c(S^p_{A_i}/G^n_i[k])$. Then $\sigma^r_{i,an}$ should be $\sigma^r_{i,cb}\in\Sigma_{i,cb}$ from $R(l_{ao}(S^p_{A_i}/G_i[k]))\in R_{FT_{i,i+1}}[k]$, so it follows that $\exists\sigma^t_{i+1,cm}\in\Sigma_{i+1,cm}$ with $\mu(\sigma^t_{i+1,cm})=\mu^c(\sigma^r_{i,cb})$. These are mapped into K_{i+1} through $h(\cdot,\cdot)$ and the corresponding agent supervisor $S^p_{A_{i+1}}$ reconfigured as in the above over $G^n_{i+1}[k]$ subsequent to $S^p_{A_i}/G_i[k]$ generates $R(l_{ao}(S^p_{A_i}/G_i[k])K_{i+1})=R(l_i^1\sigma^r_{i,cb}l_i^2l^1_{i+1}\sigma^t_{i+1,cm}l^2_{i+1})=R(l_i^{1'}\ l_i^{2'}\ l^{1'}_{i+1}\ l^{2'}_{i+1})\in R(L_{FT_{i,i+1}}[k])$ for some $l_i^{1'},l_i^{2'}\in\Sigma^*_{i,n}$ and $l^{1'}_{i+1},l^{2'}_{i+1}\in\Sigma^*_{i+1,n}$ following Proposition 1 where $l_i^1,l_i^2\in\Sigma^*_{i,n}l^1_{i+1},l^2_{i+1}\in\Sigma^*_{i+1,n}$ After all, any fault propagated from $G_i[k]$ can be eliminated by $S^p_{A_{i+1}}$ in this way. Hence we achieve the mutual fault-tolerance between $G_i[k]$ and $G^n_{i+1}[k]$ accordingly.

V. A Case Study of Polypropylene Prepolymerization and Polymerization Processes

In this section, we study the multiagent fault-tolerant supervisory control of polypropylene prepolymerization and polymerization processes with partial observations under investigation of a pilot plant in the petrochemical industry. The polypropylene polymerization process is a kind of petrochemical process producing the polypropylene [17] from the propylene by polymerization and composed of several unit processes such as a prepolymerization process, a polymerization process, and posterior processes connected in serial as illustrated in Fig. 3 The propylene and MUD/TEAL/Donor mixture are fed into the prepolymerization reactor and then transferred to the polymerization reactor together with the hydrogen, propylene, ethylene, and Butene-1. Polymers are formed in the polymerization process under specific reaction conditions and the polypropylene is finally produced after several posterior processes. In the following, we consider the prepolymerization and polymeri-

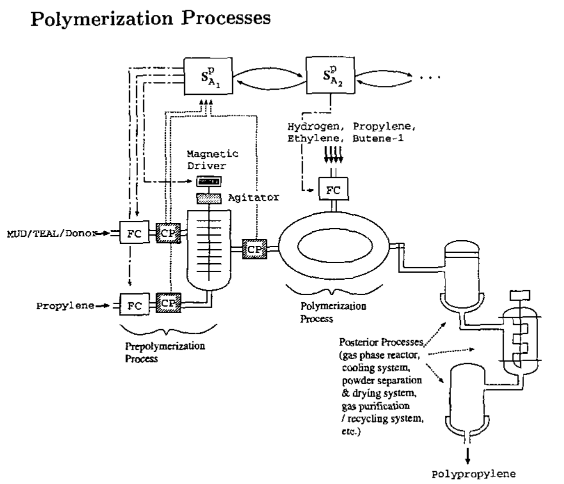

그림 3. 폴리프로필렌 예비중합공정과 중합공정의 다이어그램

Fig. 3. Schematic diagram of polypropylene prepolymerization and polymerization processes.

zation processes. The prepolymerization reactor is operated under the specific nominal reaction conditions of 20°C(temperature), 34.5kg/cm^{2}g (pressure), and 4 min (residence time), and the polymerization reactor is nominally operated under 70°C (temperature), 32.5-33.6 kg/cm^{2}g (pressure), and 50% wt (polymer density/slurry). The material feed rates are controlled by flow controllers (FCs), and the viscosity of slurries in the mixture is controlled by the agitator in the prepolymerization reactor and also by the density of hydrogen in the polymerization reactor, respectively. Suppose that the FCs and the agitator of the prepolymerization reactor are subject to abnormal events which cause *instantaneous deviation from the nominal set* values. Let $G_i[k]$ be the automaton of the process in the prepolymerization reactor (i=1) and the polymerization reactor (i=2) in view of flow control and slurry viscosity control. Figure 4 illustrates the component DEMs of $G_1[k]$ and $G_2^n[k]$. In Fig. 4, the states of $G_1[k]$ are composed of IV_1^y (Initial Value of y in $G_1[k]$), LV_1^y (Lower Value of y in $G_1[k]$), NV_1^y(Nominal

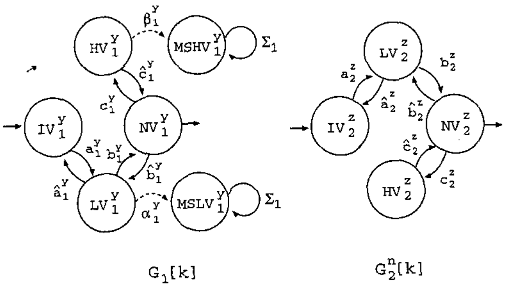

그림 4. $G_1[k]$ 과 $G_2^n[k]$의 성분 이산사건모델들 [y: m (MUD/TEAL/Donor), p(Propylene), a(Agitator Speed) ; z :p(Propylene), h (Hydrogen)]

Fig. 4. Component DEMs of $G_1[k]$ and $G_2^n[k]$ [y: m(MUD/TEAL/Donor), p(Propylene), a (Agitator Speed) ; z :p (Propylene), h (Hydrogen)].

Value of y in $G_1[k]$), HV_1^y (Higher Value of y in $G_1[k]$), $MSLV_1^y$ (Momentarily Stuck to Lower Value of y in $G_1[k]$), and $MSHV_1^y$ (Momentarily Stuck to Higher Value of y in $G_1[k]$), where y represents one of m('MUD/TEAL/Donor'), p ('Propylene'), and a('Agitator Speed'). The events of $G_1[k]$ consist of the normal controllable and observable events of a_1^y, $\hat{a}_1^y$, b_1^y, $\hat{b}_1^y$, c_1^y, $\hat{c}_1^y$, and the unobservable abnormal events of α_1^y, β_1^y. The states of $G_2^n[k]$ comprise IV_2^z, LV_2^z, NV_2^z, HV_2^z and the events of it consist of the normal controllable events of a_2^z, $\hat{a}_2^z$, b_2^z, $\hat{b}_2^z$, c_2^z, $\hat{c}_2^z$, where z represents either p ('Propylene') or h ('Hydrogen'). Therefore, we know that $\Sigma_1=\Sigma_{1,n}\cup(\Sigma_{1,an}\cap\Sigma_{1,uo})=\{a_1^y, \hat{a}_1^y, b_1^y, \hat{b}_1^y, c_1^y, \hat{c}_1^y\}\cup\{\alpha_1^y, \beta_1^y\}$ and $\Sigma_{2,n}=\{a_2^z, \hat{a}_2^z, b_2^z, \hat{b}_2^z, c_2^z, \hat{c}_2^z\}$. Note that the instantaneous deviation of the propylene feed rate and the agitator speed from the nominal values in the prepolymerization reactor can be compensated by adjusting the propylene feed rate and the hydrogen feed rate in the polymerization reactor, respectively, in view of overall polymerization process conditions. However, certain deviation of the MUD/TEAL/Donor feed rate from the tolerance range of the nominal value in the prepolymerization reactor can not be complemented by any measure in the polymerization reactor. Hence, we know $\Sigma_{1,an}(=\Sigma_{1,an}\cap\Sigma_{1,uo})=\Sigma_{1,cb}\cup\Sigma_{1,ucb}=\{\alpha_1^p, \beta_1^p, \alpha_1^a, \beta_1^a\}\cup\{\alpha_1^m, \beta_1^m\}$. From these, the domain of fault-tolerance of $G_2[k]$ becomes $R_{FT_2}[k]=\{(q_1^m, q_1^p, q_1^a)\in Q_1 \mid q_1^m \notin\{MSLV_1^m, MSHV_1^m\}\}$ where q_1^m, q_1^p, q_1^a represent the states of the component DEM of $G_1[k]$. Let the complementary measure function $\mu:\Sigma\mapsto\Re$ be defined for $\Sigma_{1,cb}$ and $\Sigma_{2,cm}$ as appeared in CMT of Table 1 where the binary number is used. Under normal operating conditions of $G_1^n[k], K_1$ is chosen to be

표 1. $\Sigma_{1,cb}$과 $\Sigma_{2,cm}$에 대한 CMT

Table 1. CMT for $\Sigma_{1,cb}$ and $\Sigma_{2,cm}$.

$\Sigma_{1,cb}$	μ	$\Sigma_{2,cm}$	μ
α_1^p	00	c_2^p	11
β_1^p	01	$\hat{b}_2^p$	10
α_1^a	10	$\hat{b}_2^h$	01
β_1^a	11	c_2^h	00

$a_1^m b_1^m a_1^p b_1^p a_1^a b_1^a$ to satisfy the nominal reaction conditions. However, suppose α_1^p and β_1^a occur at kth operation such that $l_{ao}(S^p_{A_1}/G_1[k])=a_1^m b_1^m a_1^p \alpha_1^p a_1^a b_1^a c_1^a \beta_1^a$ due to $G_1^f[k]$. In this case, the observed sequence becomes $P(l_{ao}(S^p_{A_1}/G_1[k]))=a_1^m b_1^m a_1^p a_1^a b_1^a c_1^a$ where $P:\Sigma_1^*\mapsto\Sigma_{1,o}^*$. However, we can identify α_1^p and β_1^a from $\nu(\alpha_1^p)=\nu(\beta_1^a)=1$ at kth operation for each case of $\lambda(\sigma^{k-1})=0$ or 1, $\nu(\sigma^{k-1})=0$ or 1, $\sigma^{k-1}\in\{\alpha_1^p, \beta_1^a\}$ at $(k-1)$th operation, following UFI Algorithm. Physically, $\lambda(\sigma^k)$ is available from the comparator (CP) output, which corresponds to the difference information of the controlled results. In addition, the identified abnormal status of $(\alpha_1^p, (NV_1^m, LV_1^p, IV_1^a))$ and $(\beta_1^a, (NV_1^m, MSLV_1^p, HV_1^a))$ is classified into a fault, so there exists K_2 on which $S^p_{A_2}$ can be reconfigured to meet the mutual fault-tolerance between $G_1[k]$ and $G_2^n[k]$ since $R(l_{ao}(S^p_{A_1}/G_1[k]))\in R_{FT_2}[k]$ from Proposition 1. Therefore, the feedback information $g_2(l_{ao}(S^p_{A_1}/G_1[k]))$ returns 1 to continue the current process without interruption. The reconfiguration of $S^p_{A_2}$ can be done as follows: Let $f^e:\Sigma\times Q\mapsto\Re$ be defined as $f^e(\sigma_n, q)=b_n$ for $\sigma_n\in\Sigma$ and q in Q with the binary number $b_n=b_n^1 b_n^2\cdots b_n^{od(|\Sigma|)}$ where $b_n^i\in\{0,1\}$, $i\in[1, od(|\Sigma|)]$, and $od(N)=M$ such that $2^{M-1}<N\leq 2^M$ in case of no duplication between the occurrence of events. Moreover, let $f(l)=b_l$ with $b_l=b_1 b_2\cdots b_{|l|}$ where $b_n=f^e(\sigma_n, q)$, $n\in[1,|l|]$ for $l=\sigma_1\sigma_2\cdots\sigma_{|l|}$, and $\eta:\Re\mapsto\Re$ be defined as $\eta(f^e(\sigma_n, q))=f^e(\sigma_n, q)+2^0$ in the binary representation. From $od(|\Sigma_1|)=5$, let, e.g., $f^e(a_1^m, q_1^0)=00001, f^e(b_1^m, q_1^1)=00010, f^e(a_1^p, q_1^2)=00011, f^e(b_1^p, q_1^3)=00100, f^e(a_1^a, q_1^4)=00101, f^e(b_1^a, q_1^5)=00110, f^e(c_1^a, q_1^9)=01001, f^e(\alpha_1^p, q_1^3)=00110, f^e(a_1^a, q_1^7)=00111, f^e(b_1^a, q_1^8)=01000, f^e(c_1^a, c_1^9)=01001, f^e(\beta_1^a, q_1^{10})=01011, f^e(a_2^p, q_2^0)=00001, f^e(b_2^p, q_2^1)=00010, f^e(a_2^h, q_2^2)=00011, f^e(b_2^h, q_2^3)=00100, f^e(c_2^p, q_2^2)=00101, f^e(a_2^h, q_2^5)=00110, f^e(b_2^h, q_2^6)=00111, f^e(c_2^h, q_2^7)=01000$ where $q_1^i\in Q_1, i\in[1,|Q_1|]$ and $q_2^j\in Q_2, j\in[1,|Q_2|]$ are described in Table 2. Then $f(l_{ao}(S^p_{A_1}/G_1[k]))=$ 0000100010000110011000111010000100101011 and we know $f^e(\alpha_1^p, q_1^3)\neq\eta(f^e(a_1^p, q_1^2))$ with $\alpha_1^p\in\Sigma_{1,an}$ and $f^e(\beta_1^a, q_1^{10})\neq\eta(f^e(c_1^a, q_1^9))$ with $\beta_1^a\in\Sigma_{1,an}$. Since $\mu(c_2^p)=\mu^c(\alpha_1^p)$ and $\mu(c_2^h)=\mu^c(\beta_1^a)$ from CMT, we can formulate K_2 such that $f(K_2)=f^c(l_{ao}(S^p_{A_1}/G_1[k]))$ as $K_2=a_2^p b_2^p c_2^p a_2^h b_2^h c_2^h$. Therefore, it becomes $R(l_{ao}(S^p_{A_1}/G_1[k])K_2)=R(a_1^m b_1^m a_1^p \alpha_1^p a_1^a b_1^a c_1^a \beta_1^a a_2^p b_2^p c_2^p a_2^h b_2^h c_2^h)=R(a_1^m b_1^m a_1^p b_1^p a_1^a b_1^a a_2^p b_2^p a_2^h b_2^h)$, which assures the mutual fault-tolerance between $G_1[k]$ and $G_2^n[k]$.

In the other respect, if $G_1^f[k]$ contains α_1^m(or

β_1^m) then it can also be identified by $\nu(\alpha_1^m)=1$(or $\nu(\beta_1^m)=1$) from UFI Algorithm. and it results in $l_{ao}(S^p_{A_1}/G_1[k]) = a_1^m \alpha_1^m a_1^p b_1^p a_1^a b_1^a$ (or $a_1^m b_1^m c_1^m \beta_1^m a_1^p b_1^p a_1^a b_1^a$). Further, ($\alpha_1^m$, q_1^1) (or (β_1^m, q_1^{12})) turns out to be a failure in this case from $R(l_{ao}(S^p_{A_1}/G_1[k])) \not\in R_{FT_2}[k]$. Physically, it means that an instantaneous deviation of the MUD/TEAL/Donor feed rate from the nominal set value in the prepolymerization reactor can not be compensated by any measure of the polymerization reactor. Hence, $g_2(l_{ao}(S^p_{A_1}/G_1[k]))$ returns 0 requiring $S^p_{A_1}$ to stop the current process promptly and to do the failure diagnosis.

표 2. $G_1[k]$과 $G_2^n[k]$의 부분적 성분 이산사건모델들에 대한 상태정의

Table 2. States definition for parts of DEMs of $G_1[k]$ and $G_2^n[k]$.

Q_1	Contents	Q_2	Contents
q_1^0	(IV_1^m, IV_1^p, IV_1^a)	q_2^0	(IV_2^p, IV_2^h)
q_1^1	(LV_1^m, IV_1^p, IV_1^a)	q_2^1	(LV_2^p, IV_2^h)
q_1^2	(NV_1^m, IV_1^p, IV_1^a)	q_2^2	(NV_2^p, IV_2^h)
q_1^3	(NV_1^m, LV_1^p, IV_1^a)	q_2^3	(NV_2^p, LV_2^h)
q_1^4	(NV_1^m, NV_1^p, IV_1^a)	q_2^4	(NV_2^p, NV_2^h)
q_1^5	(NV_1^m, NV_1^p, LV_1^a)	q_2^5	(HV_2^p, IV_2^h)
q_1^6	(NV_1^m, NV_1^p, NV_1^a)	q_2^6	(HV_2^p, LV_2^h)
q_1^7	$(NV_1^m, MSNV_1^p, IV_1^a)$	q_2^5	(HV_2^p, NV_2^h)
q_1^8	$(NV_1^m, MSLV_1^p, LV_1^a)$	q_2^8	(HV_2^p, HV_2^h)
q_1^9	$(NV_1^m, MSLV_1^p, NV_1^a)$		
q_1^{10}	$(NV_1^m, MSLV_1^p, HV_1^a)$		
q_1^{11}	$(NV_1^m, MSLV_1^p, MSHV_1^a)$		
q_1^{12}	(HV_1^m, IV_1^p, IV_1^a)		

Ⅵ. Conclusions

In this paper, we have considered the problem of multiagent fault-tolerant supervisory control of serial production systems under partial observation. To resolve the problem, we have proposed an unobservable fault identification scheme utilizing the difference information of the controlled results and the synthesis of agent supervisors guaranteeing the mutual fault-tolerance between cascaded unit processes based on the fault identification. The major characteristic of the proposed scheme lies in the fact that it allows as much autonomy as possible for each agent supervisor and the least shared information between agent supervisors cooperating for overall goals in view of mutual fault-tolerance. The emphasis has been on the case study of the fault-propagation control of polypropylene prepolymerization and polymerization processes.

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