論　文

Automatic Diagnostic Rule Generation for Rule-Based Controllers by Qualitative Sensitivity Analysis

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We introduce the Qualitative Sensitivity Analysis (QSA) technique and its application to generate automatically diagnostic rules for systems modeled in rule based causal format. The rule set is composed of atomic propositions. First, we introduce the Modified Causal Ordering (MCO) technique to derive ordering among the propositions. The result of MCO are complete subsets of propositions and Ordinal Reachability Graph (ORG). Each complete subset is identified by its ranking code. In QSA, propositions stand for the landmarks of the qualitative variables. QSA begins with the ORG and replaces the propositions with their equivalent landmarks. Perturbation is modeled by forcing a landmark to shift to its neighboring landmark. Sensitivity is identified as a consequence of perturbation, forcing two or more of the landmarks of a variable having the same rank. QSA can derive the sensitivity of the higher rank landmark due to perturbation affecting the lower rank ones. Applicability of the method is demonstrated through an example.

Key words: Qualitative reasoning, Causal ordering, Sensitivity, Perturbation

1. Introduction

In this paper we introduce a method to generate diagnostic rules from the model of normal system based on system's components malfunction. As the problem domain we focus on rule-based controllers for two reasons: first, their wide spread application (including fuzzy and expert controllers) and second, the requirement for higher reliability through automatic system diagnosis techniques. Qualitative approach is selected because in most of the rule-based systems the model can not be replaced by exact mathematical expressions, therefore not suitable for quantitative study.

Conventionally, there are two possible strategies for diagnostic rule generation: symptomatic (experience based) and topological (model based)[4]. Symptomatic method is based on the system's model of malfunction and is efficient for faults with previous record. Even the most efficient symptomatic based algorithms, fail when posed to novelfaults[8][9]. Topological method, on the other hand, is based on model of the normal system and suitable for novel faults.

Fault detection problem is formulated as follows: Given information are the model of the normal system, Ω, a set of predicted behaviors, Γ, and the possible components' malfunctions, Ψ. Ω and Ψ together are sufficient to derive another set of behaviors of the faulty system, Γ^*, different from Γ. The problem is developing diagnostic rules based on the identified discrepancies between Γ and Γ^*. Qualitative Sensitivity Analysis (QSA) is a general purpose technique to fulfill this scenario.

The main portion of this paper (Sections 2 and 3) is devoted to introduce the Modified Causal Ordering (MCO) and QSA. MCO serves as the backup method whose results are directly used in QSA.

We begin with a class of rule based systems represented by Eq. (1).

$$\Phi(X) \rightarrow Y; \quad \cdots\cdots (1)$$

Where X and Y stand for the cause and effect sets of atomic propositions, respectively. Φ is the working matrix indicating how the propositions are related. In MCO we extract the propositions that can potentially take part in ordering, derive the complete subsets[6], which resemble the intermediate stable states of the truth propagation, and organize them in the Ordinal Reachability Graph (ORG). All nodes of the ORG possess an ordering rank (r_k) due to their appearance in the complete subsets.

ORG serves as the working model for QSA. We assume that each proposition addresses a landmark of a qualitative variable. In QSA we replace the propositions with the landmarks and define sensitivity, qualitatively, in terms of shifting among the landmarks. Our definition of sensitivity is the qualitative version of what is known as sensitivity of a quantity Q to perturbation in a parameter P, defined by:

$$(\partial Q/\partial P)(P/Q) \quad \cdots\cdots (2)$$

In Section (4) QSA is applied to generate diagnostic rules in a detailed example. We conclude with comments on further extensions of the method in Section 5.

2. Modified causal ordering technique (MCO)

Causality is a universal relation holding among the propositions 〔Def. 1〕 in a model of standard logic. Causal ordering is a method to deduce complete subset of variables for a set of self-contained qualitative equations[6]. Modified Causal Ordering (MCO) is a method to deduce complete subset of propositions for a set of self-contained rules. Complete subsets are ranked. Intuitively, all propositions of the complete subset of rank r_k can be causally deduced from the lower ranked subsets[6]. Higher ranked complete subsets imply deeper level of causal propagation of truth. In terms of behavioral interpretation, causal ordering resembles decomposition of behavior of a complex system to stable states and distinguishing the interaction among and within those states. Because of the reversibility property of equality (=) in equations, as compared to implication (→) in rules, the conventional causal ordering technique falls short to develop correct ordering, specially for the system with structural defects*1.

MCO is a technique exclusive to rule based systems, for producing the hierarchical structure of the truth propagation due to a given initial conditions. The results of MCO are complete subsets of propositions, which resemble the intermediate stable states of truth propagation, and Ordinal Reachability Graph (ORG). We introduce them below.

〔**Assumption 1**〕 Causality[1][11]

Causality implies universal relation, sufficient conditionality but no strict implication. ■

(→) is the symbol for causal relation. For the expression "$p \rightarrow q$", universal relation means validity over an interval. Causal relation is a sufficient condition because validity of p implies validity of q. But it is not strict implication, because one can neither say that p is necessary for q, nor from the validity of q one can reason about validity of p. All systems studied here are supposed to be intrinsically causal.

〔**Defnition 1**〕 Proposition[1][11]

Proposition is an atomic sentence which is empirically true and logically independent from the other propositions. ■

By empirical truth we mean that propositions are physically realizable and comply with the universal physical rules (i.e., conservation of energy, etc.). This assumption excludes the proposition such as: 2+2=5. Logical independence means that no single expression composed of the propositions is self-contradictory. We will see later that each proposition stands for the landmark of a qualitative variable.

Rules are composed of propositions. A set of causal rules is called uniform if all of the rules

*1: Structural defects of a rule based system are inconsistency, acausality and loop.

*2: Rules can potentially fall into three categories:
1.Global causal rules;
(causal rules without reversal)[1][11].
2.Necessity (□)/Possibility (◇) rules[2];
3.Local causal rules;
(causal rules with reversal)[1][11].

belong to a single category*2. In this paper we consider only the global causal rules, i.e., causal rules without reversal[1][11].

〔**Definition 2**〕 Rule based system

A rule based system is represented by Eq. (1).

X and Y are (m) and (n) dimension vectors standing for cause and effect propositions, respectively.

$$X \subseteq P\,;\ Y \subseteq P\,;\ \text{and}\ X \cup Y = P; \quad \cdots\cdots\cdots (3)$$

P is the proposition set;

Φ is the $(n \times m)$ dimensional binary "working matrix". For the rule ρ_i:

$\forall \phi_{ij} \in \Phi$,

$\phi_{ij}=1$;if the cause x_j is specified for the effect y_i.

$\phi_{ij}=0$; otherwise. ■

〔**Definition 3**〕 Initial fact set

Initial facts are independent atomic propositions belonging to the set of causes, X, but not to the set of effects, Y.

$$F=\{p|(p \in X) \wedge (p \notin Y)\} \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

Facts are supposed to be empirically true. ■

A set of rules is called self contained [6] if the number of independent rules is sufficient to derive the truth of all the propositions due to given initial facts. Self containment condition is highly dependent to the given initial facts. The following propositions indicate which propositions and rules can potentially take part in ordering.

〔**Proposition 1**〕 Proper proposition set (P_0)

For any given initial fact set, F, the proper proposition set, P_0, (i.e., those potentially participating in causal ordering) is composed of those propositions belonging to the union of initial fact (F) and effect set (Y). ■

$$P_0=\{p_0|p_0 \in F \cup Y\}; \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

〔**Proposition 2**〕 Proper rule set (ρ_0)

For any given initial fact set F, *a* subset of rules $\rho_0 \subseteq R$, is called proper if its building propositions are all from the proper proposition set.

$$\rho_0=\{R|\forall \rho \in R,\ p \in P_0\} \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

R is the given rule set. ■

MCO technique is applied to P_0 in order to deduce its complete subsets[6].

〔**Definition 4**〕 Ranking

(1) Rank (r) is the equivalence code for the complete subset of propositions denoting the depth of causal propagation of truth.

$$\left.\begin{array}{l} r: P_k \rightarrow I \\ \forall p \in P_0,\ \text{if}\ p \in P_k\ \text{then}\ r(p)=k; \end{array}\right\} \cdots\cdots (7)$$

I is the non-negative ordered integer set;

P_k is the K^{th} complete subset;

(2) Minimal complete subset (P_m) is the lowest ranked subset of P_0.

(3) Conclusion (P_M) is the complete subset with the highest rank. ■

We assume that $P_m=F$.

Ordinal Reachability Graph (ORG) represents the structure of the rule based system.

〔**Definition 5**〕 Ordinal Reachability Graph (ORG)

Ordinal Reachability Graph (ORG) is a constraint network composed of nodes standing for the proper propositions, P_0, and binary arcs.

$$\text{ORG}=(P_0,\ A,\ r,\ F) \quad \cdots\cdots\cdots\cdots\cdots\cdots (8)$$

P_0 set of proper propositions.

A set of arcs. Every arc is addressed by a binary code $Z=\{1, 0\}$. For any pair of propositions, p_i and p_j,

$Z=1$; if they are related as the cause and effect of a rule.

$Z=0$; otherwise*3.

r ranking code. All of the nodes of the ORG possess an ordering rank (r_k) due to their appearance in the complete subsets.

F set of initially given facts. ■

〔**Lemma 1**〕 Rules of inference for ORG

(1) Modus ponents:

From p and $p \rightarrow q$, derive q; $\cdots\cdots\cdots\cdots$ (9)

(2) Hypothetical syllogism:

From $p \rightarrow q$ and $q \rightarrow r$, derive $p \rightarrow r$; $\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$ (10)

(3) Disjunctive syllogism;

From $p \vee q$ and $\neg p$, derive q; $\cdots\cdots\cdots$ (11)

(4) Conjunction : From p and q, derive $p \wedge q$; $\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$ (12)

(5) Addition : From p, derive $p \vee q$; $\cdots\cdots$ (13)

(6) Subtraction : From $p \wedge q$, derive p; (14)

■

*3 : Arcs addressed by 0 are shown on QFG.

MCO algorithm can deduce the complete subsets. In MCO in order to remove the ambiguity between the causes and effects in Φ, we can assign two digit binary codes (10) for the propositions appearing as the "cause" and (01) for the "effect" part of a rule. Facts are also treated as (01) items. This coding overcomes the ambiguity. The following lemma explains the MCO algorithm.

〔**Lemma 2**〕 MCO algorithm

For the proper rule set, ρ_0, proper proposition set, P_0, and the initial fact set, F, composed of (K), (M) and (N) elements, respectively:

(1) Construct the $(M\times M)$ matrix, Φ^*, whose columns denote propositions $p\in P_0$, and the rows are rules, ρ_0, and F, initial fact set. The self containment condition is specified by:

$$\left.\begin{array}{l} M=K+N. \\ \forall\, \Phi_{nm}\in\Phi \end{array}\right\} \qquad (15)$$

$\theta_{nm}=01$ if either the proposition p_m appearing in the effect part of a rule, ρ_k, or as a fact F_n.

$\theta_{nm}=10$ if the proposition P_m appearing as the condition part of a rule ρ_k.

$\theta_{nm}=0$ otherwise.

(2) F is the minimal complete subset. Check the columns of Φ^* for those propositions appearing in F.

$\forall m,n[(F_n, p_m)=(01, 10)]\rightarrow(\rho_k, p_m)$:ACTIVE Save these (ρ_k, p_m) in the ACTIVE list.

(3) For the ACTIVE list of (ρ_k, p_m):

(a) $\forall k$(vertical search):

(01)→(10):The effect of a rule proved true or a valid fact, can be the cause for some other rule.

(01)→(01):The effect of a rule can be deduced from a valid fact or effects of the other rule proved true.

(b) $\forall m$(Horizontal search):

Σ(10)→(01):Satisfaction of all the conditions of a rule is sufficient for propagating the cause to the effect.

(4) Save the consequence in the S_r (Complete Subset of r^{th} order).

(5) For $r\geqq 2$ repeat from Step 2, replacing minimal subset with subsets of order $(r-1)$. ■

The results of MCO are directly used in QSA which we introduce in the next section.

3. Qualitative sensitivity analysis(QSA)

In QSA we replace propositions with landmarks. We identify sensitivity in terms of shifting among the landmarks of the qualitative variables. Suppose that there are (m) qualitative variable with the finite ordered landmarks:

$$\left.\begin{array}{l} V_1:(L_{V11},\ L_{V12},\ L_{V13},\cdots) \\ V_2:(L_{V21},\ L_{V22},\ L_{V23},\cdots) \\ \cdots\cdots\cdots\cdots \\ V_m:(L_{Vm1},\ L_{Vm2},\ L_{Vm3},\cdots) \end{array}\right\} \qquad (16)$$

As we do not consider temporal issues is this paper, the terms *landmark* and *landmark value* can be used interchangeably, By landmark we mean the value of the continuous qualitative variable 〔Def. 6〕. For discrete variables, landmarks are the symbols from a finite ordered* set of states.

The advantage of working with landmarks instead of propositions is that perturbation can have physical interpretation in terms of landmarks. In other words any single qualitative variable can appear in a number of propositions, each addressing one of its landmarks. Therefore shifting among the landmarks can be explained even if their corresponding propositions have no apparent relation in the form of a rule.

The idea of sensitivity analysis is roughly as follows: suppose that some perturbation is introduced to a landmark, say L_{Vi2}, with the neighboring landmarks L_{Vi1} and L_{Vi3}. *Perturbation* is defined qualitatively as forcing a landmark to be shifted to its immediate neighboring ones. The propositions addressing neighboring landmarks, L_{Vi1} and L_{Vi3}, are added to the fact set. Then MCO can derive the new ordering due to the new initial facts. This leads to a new perturbed ordinal reachability graph (ORG_p) which we prove that the original ORG resides in it. This means that ORG_p envisions some extra landmarks which were not visible before. In ORG_p for a complete subset of rank r, if two or more neighboring landmarks of a variables, V_m, happens to have the same rank, i.e., L^r_{Vm1} and L^r_{Vm2},

* 4 : Ordered set of states means that for each state, its preceding and succeeding states are specified.

their corresponding propositions are called sensitive to perturbation introduced to L_{Vi2}.

Relation among " propositions", "qualitative variables" and "landmarks" is defined below.

〔**Definition 6**〕 Qualitative variable

(1) A continuous qualitative variable is a single valued function of an independent variable (say time) and has an associated finite closed ordered set of landmarks. Each landmark has two attributes: distinguished time point and the landmark value.

$$V_m :[(L_{Vm1},\ T_{Vm1}),\ (L_{Vm2},\ T_{Vm2}),\cdots] \quad \cdots\cdots(17)$$

(2) A discrete qualitative variable is represented by a finite ordered set of symbolic landmarks.

$$V_m :(L_{Vm1},\ L_{Vm2},\ L_{Vm3},\cdots) \quad \cdots\cdots(18)$$

■

For discrete qualitative variables "ordered" set means that for each landmark the preceding and succeeding landmarks are specified. As explained earlier, we use the terms landmark and landmark value interchangeably. The next assumption indicates that landmarks and propositions can be used interchangeably (See Fig. 2).

〔**Assumption 2**〕 Propositions and landmarks

There is a one to one relation between the atomic propositions and landmarks, i.e., each atomic proposition addresses one and only one landmark of a qualitative variable and vice-versa. ■

〔**Assumption 3**〕 Qualitative landmark shifting

Any landmark of a variable can only be shifted to its next immediate ones. ■

This assumption limits the effects of the external world to infinitesimal perturbation. For continuous qualitative variables the mean value and continuity theorems[7] already limt the change to the intermediate landmarks only. Therefore this assumption mainly addresses discrete qualitative variables.

We can derive the OGR_p, by applying MCO, due to landmark shift, and based on 〔Assumptions 2, 3〕 we can prove that ORG_p is the upwards compatible version of the original ORG.

〔**Definition 7**〕 Upward compatibility

OGR_2 is the upward compatible version of ORG_1, if:

$$ORG_1=(P_0,\ A_1,\ r_1,\ F_1) \quad \cdots\cdots(19)$$

$$ORG_2=(P_0,\ A_2,\ r_2,\ F_2) \quad \cdots\cdots(20)$$

$$A_1 \subseteq A_2 \text{ and } F_1 \subseteq F_2 \quad \cdots\cdots(21)$$

A_1 set of arcs;

F_1 set of initial facts; ■

〔**Theorem 1**〕

For the set of proper propositions P_0, the perturb-ed ORG_p is the upward compatible version of the original ORG.

(Proof)

All arcs of ORG are arcs of ORG_p, because in propositional calculus, for the proposition set P_0, all deductions from a set of given facts F, are valid for another set F^*, if $F \subseteq F^*$. Otherwise, if there is a proposition, deducible from F but not from F^* implies that F is a lower ranked complete subset for P_0 not F^* and this is a conflict because $F \subseteq F^*$. ■

Based on 〔Theorem 3〕 we can define qualitative sensitivity.

〔**Definition 8**〕 Sensitivity

A landmark of the qualitative variable U, L_{iU} is called sensitive to perturbation introduced to the landmark of another qualitative variable V,L_{jV}, (i. e., shifting L_{jV} to L_{j+1V}) if for a given fact set F, the latter is originally of lower rank and if a neighboring landmark of the former, L_{i+1U}, happens to have the same rank on perturbed reachability graph, ORG_p with the L_{iU}, shown by:

$$(L_{iV},\ L_{i+1V})\S(L_{jU},\ L_{j+1U}) \quad \cdots\cdots(22)$$

Denoting that U is sensitive to V for these pair of landmarks. ■

〔**Lemma 3**〕 QSA procedure

(1) Deriving the complete subsets and ORG for a set of consistent rules due to a given fact set by means of Modified Causal Ordering (MCO).

(2) Adding the perturbed landmarks to the fact set and deriving ORG_p.

(3) Checking the complete subsets for the existence of possible sensitive higher ranked landmarks. ■

In the next section we introduce one of the applications of QSA to derive diagnostic rules for rule based systems.

4. Diagnostic rule generation for dynamic faults

For a rule based system first MCO derives the complete subsets and ORG, which serve as the model, Ω. Then for the elements of the components' malfunction set, Ψ, the new neighboring landmarks are added to the fact set and MCO derives the new ordering and ORG_p. Based on [Def. 8], sensitivity is checked to see if there are two or more landmarks of a parameter of the same rank. Suppose that p, q, r and s and the corresponding propositions of the landmarks L_{iV}, L_{i+1V}, L_{jU} and L_{j+1U} in Eq(22), respectively. If p and r are propositions representing the original relation, then diagnostic rule can be: "If s, then possible cause of malfunction is q".

$$s \rightarrow \Diamond q; \quad \cdots\cdots (23)$$

Diagnostic rules generated in this way can be used for further symptomatic diagnosis. An advantage of this method is its ability to cope with concurrent perturbations and multiple causes.

Let's examine the control rules of the double fuel tank system[12] shown in Fig.1. Fuel can be pumped from one tank to the other due to the pressure differences of the tanks. Control valves are V_{11}, V_{12}, V_{21}, V_{22} and V_{33}. The propositions are:

α : V_{12} open;	$\neg\alpha$: V_{12} closed;
β : V_{21} open;	$\neg\beta$: V_{21} closed;
γ : V_{11} open;	$\neg\gamma$: V_{11} closed;
δ : V_{22} open;	$\neg\delta$: V_{22} closed;
θ : pressurize T_1;	$\neg\theta$: pressure drop T_1;
η : pressure drop T_2;	$\neg\eta$: pressurize T_2;

ζ : V_3 open;

λ : fuel transfer from T_1 to T_2;

σ : fuel transfer from T_2 to T_1;

μ : No fuel transfer;

Bahavioral rules, indicating the behavior of the normal system are:

$$\rho_1:(\delta)\Lambda(\neg\beta)\rightarrow(\eta); \quad \cdots\cdots (24)$$

$$\rho_2:(\alpha)\Lambda(\neg\gamma)\rightarrow(\theta); \quad \cdots\cdots (25)$$

$$\rho_3:(\zeta)\Lambda(\eta)\Lambda(\theta)\rightarrow(\lambda);\text{otherwise}:(\mu); \quad \cdots (26)$$

$$\rho_4:(\beta)\Lambda(\neg\delta)\rightarrow(\neg\eta); \quad \cdots\cdots (27)$$

$$\rho_5:(\gamma)\Lambda(\neg\alpha)\rightarrow(\neg\theta); \quad \cdots\cdots (28)$$

$$\rho_6:(\zeta)\Lambda(\neg\eta)\Lambda(\neg\theta)\rightarrow(\sigma);\text{otherwise}:(\mu); \quad \cdots\cdots (29)$$

Suppose that the initial fact set is given:

$$F=\{\alpha,\ \neg\beta,\ \neg\gamma,\ \delta,\ \zeta) \quad \cdots\cdots (30)$$

indicating the normal set points for fuel transfer from T_1 to T_2. The proper proposition set is:

$$\left.\begin{array}{l} P_0=F\cup Y \\ P_0=\{\alpha,\ \neg\beta,\ \neg\gamma,\ \delta,\zeta,\ \theta,\ \neg\theta, \\ \quad \eta,\ \neg\eta,\ \lambda,\ \sigma,\ \mu\} \end{array}\right\} \quad \cdots\cdots (31)$$

There are 8 qualitative discrete variables with the landmark set given below:

V_{11} : $L_{1V11}=(\text{Open})_{,1}\nearrow^2$ $\quad L_{2V11}=(\text{close})_2\nearrow^1$

V_{12} : $L_{1V12}=(\text{Open})_{,1}\nearrow^2$ $\quad L_{2V12}=(\text{close})_2\nearrow^1$

V_{21} : $L_{1V21}=(\text{Open})_{,1}\nearrow^2$ $\quad L_{2V21}=(\text{close})_2\nearrow^1$

V_{22} : $L_{1V22}=(\text{Open})_{,1}\nearrow^2$ $\quad L_{2V22}=(\text{close})_2\nearrow^1$

V_{33} : $L_{1V33}=(\text{Open})_{,1}\nearrow^2$ $\quad L_{2V33}=(\text{close})_2\nearrow^1$

T_1 : $L_{1T1}=(\text{pressurize})_{,1}\nearrow^2$

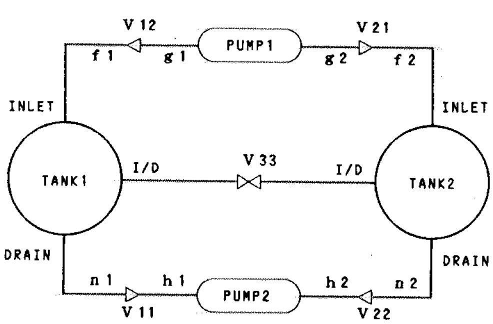

Fig.1. Simplified double fuel tank system.

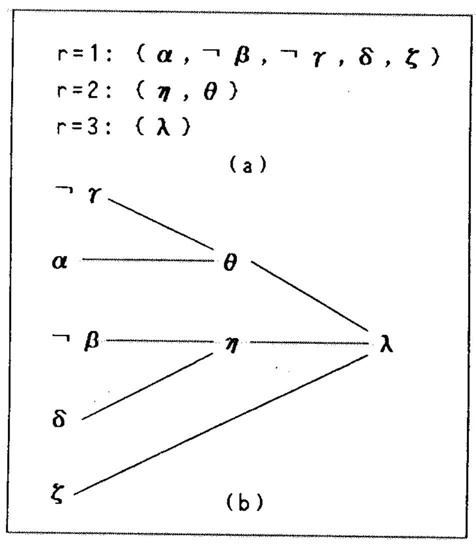

Fig.2. (a) Complete subsets, (b) original ORG.

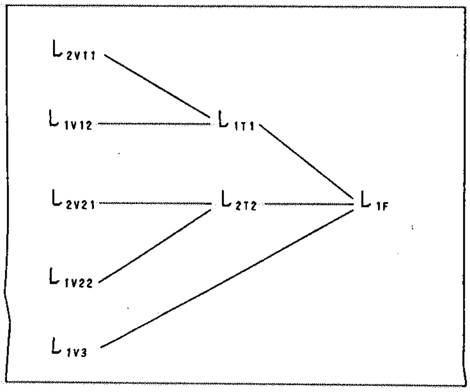

Fig.3. Original ORG when propositions replaced by the landmarks.

$$L_{2T1}=(\text{depressure})_{2}\nearrow^{1}$$
$$T_2:\ L_{1T2}=(\text{pressurize})_{,1}\nearrow^{2}$$
$$L_{2T2}=(\text{depressure})_{2}\nearrow^{1}$$
$$F:\quad L_{1F}=(T_1\rightarrow T_2)_{,1}\nearrow^{2}$$
$$L_{2F}=(\text{No transfer})_{,2}\nearrow^{3,1}$$
$$L_{3F}=(T_2\rightarrow T_1)_{3}\nearrow^{2}$$

$({}_i\nearrow^j)$indicates the ordered set of landmarks meaning that the next immediate landmark of L_i is L_j.

Fig.2 shows the complete subsets (a) and original ORG (b) derived by means of applying MCO. Fig.3 depicts the results of replacing propositions with landmarks.

The malfunction set, Ψ, is composed of the propositions holding for the neighboring landmarks of the initial set points:

$$\Psi=\{\neg\alpha, \beta, \gamma, \neg\delta, \neg\zeta\} \quad \cdots\cdots\cdots\cdots\cdots\cdots (32)$$

$\neg\gamma\rightarrow\gamma$: V_{11} leaking;

$\alpha\rightarrow\neg\alpha$: V_{12} gripped;

$\neg\beta\rightarrow\beta$: V_{21} leaking;

$\delta\rightarrow\neg\delta$: V_{22} gripped;

$\zeta\rightarrow\neg\zeta$: V_{33} gripped;

Suppose that there is a single fault "V_{12} is gripped", in other words (α) is changed to $(\neg\alpha)$ due to perturbation. Adding $(\neg\alpha)$ to the fact set and using MCO leads to a new ordering. Fig.4 depicts the new complete subsets (a) and ORG_{p1}(b).

It is shown on Fig.5 that due to gripping of V_{12}, L_{1F} and L_{2F} have the same rank, or:

$$(L_{1F},\ L_{2F})\S(L_{1V12},\ L_{2V12}) \quad \cdots\cdots\cdots\cdots\cdots (33)$$

As L_{1F} and L_{1V12} are originally related in the model of normal system (Fig.3) therefore those corresponding propositions of L_{2F} and L_{2V12} designate a new diagnostic rule.

$$\mu\rightarrow\Diamond(\neg\alpha) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (34)$$

Where $(\Diamond)$ is the symbol of possibility. This rule can be interpreted as: "Gripping of V_{12} is the possible cause of having no fuel transfer between the tanks".

If both V_{12} is gripped and V_{11} is leaking concur-rently, then additional facts are $(\neg\alpha)$ and

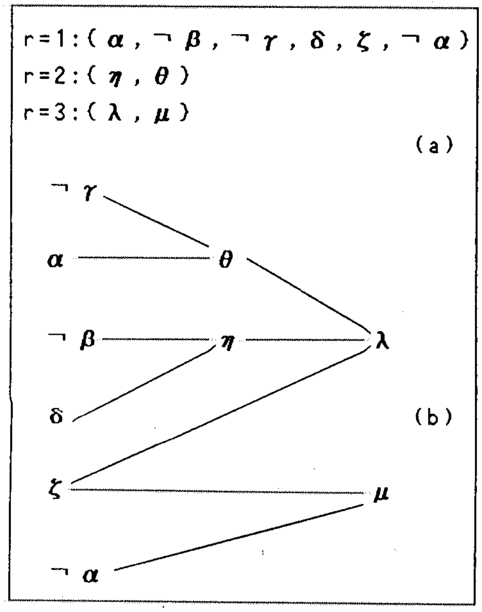

Fig.4. (a) Complete subsets, (b) perturbed ORG_{p1}.

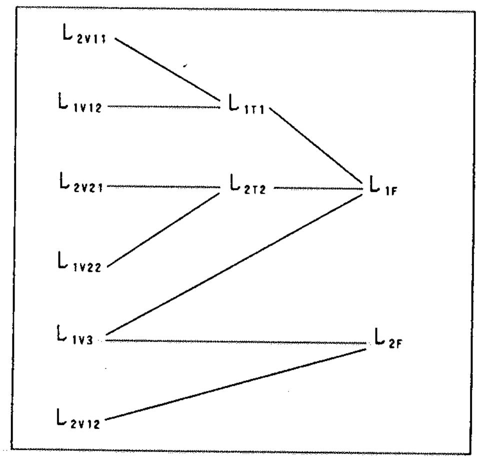

Fig.5. Perturbed ORG_{p1} when propositions replaced by the landmarks.

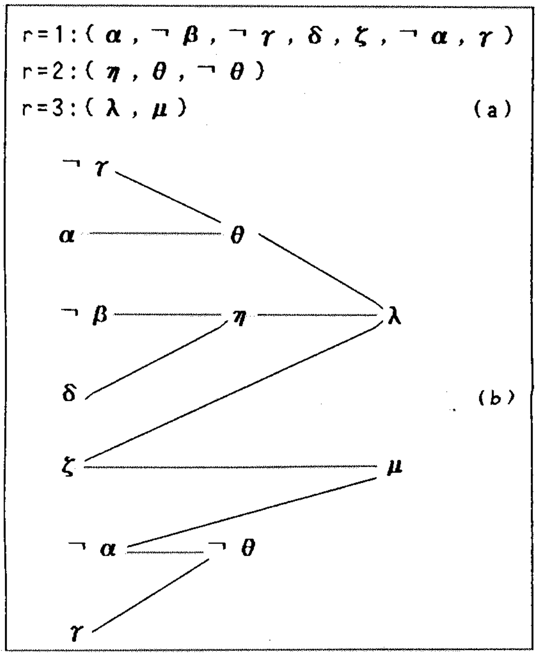

Fig.6. (a) Complete subsets, (b) perturbed ORG_{p2}.

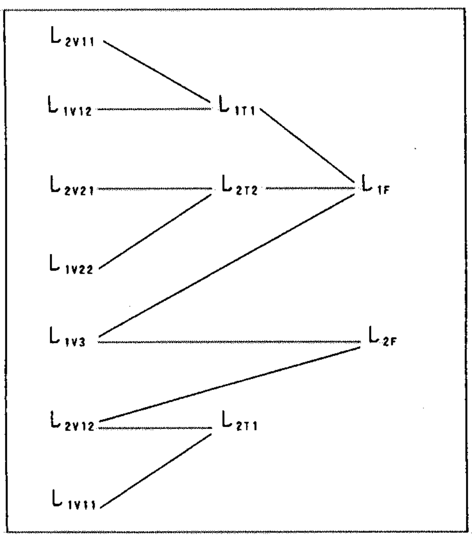

Fig.7. Rerturbed CRG_{p2} when propositions replaced by the landmarks.

(γ). The results of ordering is given in Fig.6.

Similar to the previous case, one more sensitive pair is detected.

$$(L_{1T1},\ L_{2T1})\S(L_{1V12},\ L_{2V12},\ L_{1V11},\ L_{2V11}) \quad \cdots\cdots (35)$$

$$(L_{1F},\ L_{2F})\S(L_{1V12},\ L_{2V12},\ L_{1V11},\ L_{2V11}) \quad \cdots\cdots (36)$$

And the newly generated diagnostic rule is:

$$\neg\theta \rightarrow \Diamond(\neg\alpha)\Lambda(\gamma) \cdots\cdots (37)$$

This rule can be interpreted as: "Pressure fluctu-a tion in T_1 is possibly because of the simultaneous grippage of V_{12} and leakage of V_{11}".

5. Conclusion

We introduced one of the applications of qualitative sensitivity analysis, to generate diagnostic rules from the structure of rule based systems based on system's components malfunction. This approach is unique along with two factors: First, the information of components malfunction are used to develop diagnostic rules and the outcomes can be used directly for symptomatic fault detection, which implies faster fault detection and system diagnosis. Second, the method is suitable to generate diagnostic rules for concurrent malfunctions.

The components' malfunctions are generally known in the design phase and have a very common characteristic: their existence is predictable while the time that they might come to existence is unknown. Our method can encounter this class. Obviously, similar to Ref. (4), (8) and (12), our method can not encounter those faults with their existence and time both unknown in nature.

The method suffers from general drawbacks of causal format. Generally, causal format does not necessarily restrict the rules to maintain the necessity and sufficiency, intrinsically. In a number of empirical tests[(5)] it is observed that not necessarily the causes must always increase the probability of their effects. Conventional causal format fails to explain such observation. This is known as Simpson's Paradox[(10)]. Inspired with the probablistic causality [(5)] approach, QSA can be further elabo-rated by exploiting a bi-level structural model, by introducing the infinitesimal causality. This bd-level model is specially useful for narrowing down the number of sensitive candidates.

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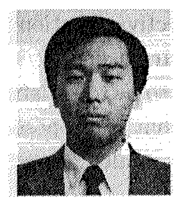

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